X-636-64-135

TM X-55049

THE ELECTRICAL CHARACTERISTICS OF IRRADIATED SILICON SOLAR CELLS AS A FUNCTION OF TEMPERATURE

MARCH 30, 1964

NASA

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

THE ELECTRICAL CHARACTERISTICS OF IRRADIATED SILICON SOLAR CELLS AS A FUNCTION OF TEMPERATURE

by

Brian T. Cunningham, Robert L. Sharp
and Luther W. Slifer

March 30, 1964

THE ELECTRICAL CHARACTERISTICS
OF IRRADIATED SILICON SOLAR CELLS
AS A FUNCTION OF TEMPERATURE

ABSTRACT

29182

The electrical characteristics of N/P (less than one ohm-cm to a nominal 10 ohm-cm base resistivity) and P/N (one ohm-cm) silicon solar cells irradiated with 1 Mev electron flux to a level of 10^{16} electrons/cm^2 have been obtained through a temperature range of -100 degrees Centigrade to +125 degrees Centigrade. The information was obtained using a tungsten light source in conjunction with a 3-centimeter water filter. Correction techniques are described to convert the spectral and intensity distributions to the air mass zero operating environment. Curves are presented which relate the power, voltage, temperature and 1 Mev electron flux level in a manner useful to the solar power supply designer.

Auth 1

THE ELECTRICAL CHARACTERISTICS
OF IRRADIATED SILICON SOLAR CELLS
AS A FUNCTION OF TEMPERATURE

SUMMARY

Satellite solar power supplies are subject to degradation from temperature and hard particle radiation. When the power supply is operating in the constant voltage mode, it is essential to choose the optimum operational voltage per cell for the space environment.

Post-irradiation electrical measurements were made on N/P (less than 1 ohm-cm to a nominal 10 ohm-cm base resistivity) and P/N (1 ohm-cm base resistivity) state-of-the-art (1962) silicon solar cells. These cells had been irradiated at room temperature with 1 Mev electrons at various flux levels up to 10^{16} electrons/cm^2. The electrical characteristics of the cells were determined for the entire temperature range between -100°C and +125°C, using a tungsten light source with a 3-cm water filter. Spectral and intensity corrections can be made to obtain air mass zero equivalent outputs.

The measurements clearly show the superiority of the 10 ohm-cm N/P cell for all solar power supplies subject to appreciable amounts of irradiation. Families of curves were developed which relate the solar cell power, operational voltage, temperature and 1 Mev flux level. These curves will aid the designer in the selection of the optimum operational voltage per cell. They can be directly applied when the solar power supply is operating in the constant voltage mode and adapted through cross-plotting to a peak power or constant load system. Selection of too high an operational voltage per cell, combined with a low estimate of either solar array temperature or hard particle irradiation, can be disastrous for the power system.

THE ELECTRICAL CHARACTERISTICS
OF IRRADIATED SILICON SOLAR CELLS
AS A FUNCTION OF TEMPERATURE

Introduction

Numerous studies have been conducted to determine the effect of electron irradiation on silicon solar cells. In order to extend the knowledge already gained in this area, an investigation was undertaken to determine the electrical characteristics of irradiated silicon solar cells as a function of temperature. Consultation with individuals familiar with satellite environments indicated that a temperature range of -100°C to +125°C would be appropriate for study.

During October and November 1962, silicon N/P and P/N state-of-the-art solar cells were purchased from nine different manufacturers. All the cells received had a photovoltaic area of approximately 1.8 cm^2. Since no particular requirement was placed on base resistivity, the cells received from the producers varied from less than 1 ohm-cm to approximately 10 ohm-cm, depending on the manufacturer's production methods. The voltage current (E-I) characteristics of these cells were measured in sunlight and under tungsten illumination at, or near, room temperature. Some cells from each manufacturer were set aside for thermal and mechanical tests and thirty cells from each manufacturer were forwarded to the Naval Research Laboratory, Washington, D.C. for irradiation. Fifteen of these cells were irradiated with 1 Mev electrons in dosages varying from 10^{11} to 10^{16} electrons/cm^2. The room temperature characteristics of these irradiated cells were obtained [1] and these same cells were then made available for the temperature effects study described here.

Equipment

The experimental equipment used to collect the data is shown in Figures 1 and 2. The unit consists of a 9'' diameter aluminum temperature-controlled chamber sealed off on one end by a 3 cm thick, circulating water, cooling bath contained by 1/4'' thick plexiglass walls. The water bath also served as a filter for the tungsten source by cutting out a large amount of the undesirable infrared. The other end of the chamber was fitted with an aluminum temperature control block shown in Figure 2. The unit contains both a 340-watt, nichrome wire heater and a cooling spiral of 1/4'' aluminum tubing for the transfer of liquid nitrogen. The front of the temperature control block is a 1/2'' thick heat sink and acts as a base for the 1/8'' thick copper plate on which the cells are mounted.

The light source used in the investigation was a 300-watt tungsten filament, reflector flood bulb. The bulb was calibrated for color temperature and was operated at 2800°K in the cylindrical light chamber shown in Figure 1. The entire assembly was constructed so as to prevent stray light from affecting the test. The bulb platform was mounted on a worm screw so that the intensity of illumination on the cells could be adjusted by moving the source closer to or further away from the cells under test. All surfaces exposed to the light source were coated with optical quality black paint to prevent reflections which would disturb the uniformity of illumination. After assembly the entire 6.5 square inch area of the temperature control block was checked for illumination uniformity, using a standard solar cell as a detector and found to be uniform within 2%. The uniformity of illumination on the cells is considered better than this because they were mounted in the central 3 square inches of this area.

When in operation, the temperature chamber was evacuated to 35 microns of mercury in order to prevent any frost accumulation on the cells at the low temperatures. Temperatures were measured using three copper-constantan thermocouples calibrated over the temperature range of the tests to an accuracy of $\pm 1^\circ$C. An attempt was made to determine the cell junction temperature as closely as possible. To this end, the thermocouples were placed on the top (on the contact strip) and on the bottom of the cells, first to determine if a temperature gradient existed, and second, to find out what its magnitude might be. The data collected led to somewhat inconclusive results and further work is being performed in this area. The thermocouple outputs were initially measured with a potentiometer. Later a deflection type pyrometer was employed, which gave results nearly as accurate as those from the potentiometer with a great saving of time. At the extremes of the temperature range, an accuracy of $\pm 5^\circ$C, including errors due to temperature gradients on the cells, was obtained. This accuracy improved to within $\pm 1^\circ$C as room temperature was approached.

The solar cell electrical characteristics were measured by varying the load resistance across the cell from 1 ohm to 2500 ohms. The current flowing with the 1 ohm load across the cell is, by accepted definition, short circuit current, I_{sc}, while the voltage across the 2500 ohms is considered to be open circuit voltage, V_{oc}. The complete I-V characteristics were recorded on an X-Y plotter to obtain a permanent record.

Procedure

I-V characteristics were obtained for all cells, using both sunlight and the filtered tungsten source. For the sunlight measurements, the sun intensity was monitored with a 15-junction normal incidence pyrheliometer. The solar cell short circuit current was measured in collimated sunlight and then linearly normalized to the short circuit current for a sunlight intensity of 100 mw/cm^2. These normalized current readings were compared to the short circuit current readings obtained from measurements made on the cells at room temperature using the tungsten light source. The latter measurements were made with the illumination set at 100 milliwatts/cm^2 "sunlight equivalent." To accomplish this, a standard solar cell with a known short circuit current at 100 milliwatts/cm^2 sunlight input was used in setting the illumination level from the tungsten light source so that the same short circuit current was obtained.

Mounting of the cells was initially accomplished by heating a pretinned copper plate to the solder melting point. Four solar cells were then placed on the plate and the unit was removed to a cool heat sink as quickly as possible. Results using this system were poor. First, electrical measurements before and after mounting indicated changes in short circuit current up to 4%; and secondly, cells under test would occasionally shatter when undergoing temperature changes. To alleviate this problem, a conductive epoxy was used to bond the cell to the test plate. Curing of the epoxy at 60°C had no measurable effect on the electrical characteristics of the cells; neither was any additional series resistance evident. The epoxy held throughout the test temperature range and no cracking of the cells was observed after institution of its use.

Cells to be tested were selected at random in groups of four and mounted on the copper plate. The cells were then placed in the chamber and the illumination was adjusted to give the "pre-chamber installation" short circuit current value from the cells. The chamber was then evacuated and the temperature lowered to -110°C. Because of the comparatively large heat sink, it was found suitable to simply let the temperature drift upward while readings were taken at the desired temperature intervals. In most cases, all four I-V curves could be obtained with a variation of only ±2°C of the nominal measuring point. I-V curves were then analyzed for short circuit current, open circuit voltage, maximum power, and power at specific voltages.

Results and Discussion

The data obtained from the measurements and its analysis and interpretation will be presented in four parts. The first three parts present individual electrical parameters, i.e., short circuit current, open circuit voltage and maximum power as a function of temperature and irradiation. The final section shows the interrelationship of power, voltage, temperature and flux (P, V, T and Φ) in the manner considered most useful to the solar power supply designer.

It should be noted that the electrical parameters in the ensuing analysis are presented in absolute terms and are therefore subject to criticism from a "representative sampling" viewpoint. In defense of this approach it can be said:

1. All the available irradiated samples were temperature-tested.
2. Wherever more than one sample was available (i.e., non-irradiated cells and those irradiated to 10^{16} electrons/cm^2), favorable comparisons were obtained between similar cells throughout the temperature range.
3. There is a favorable comparison between the results obtained during these tests and earlier results obtained with a larger number of samples at room temperature.

For these reasons, it is felt that the results are, in reality, representative of large samples and the information sufficiently reliable to be extended to this application.

Short Circuit Current

The initial room temperature measurements showed that for non-irradiated cells under tungsten light, essentially the same readings were obtained as in sunlight regardless of manufacturer. However, for N/P solar cells irradiated with dosages greater than 10^{13} electrons/cm^2, the percent change as seen under tungsten light became significantly different, depending upon manufacturer, from that seen under sunlight. It should be recalled that in the N/P category several different base resistivity cells were under evaluation, ranging from less than 1 ohm-cm to more than 10 ohm-cm. Results of an earlier investigation[1] show that the higher base resistivity cells are less susceptible to radiation damage from 1 Mev electrons at room temperature. For P/N solar cells a significant difference in the results under the two light sources was observed for dosages greater than 10^{11} electrons/cm^2. The percent change in short circuit current for solar cells due to irradiation of 10^{16} electrons/cm^2 as measured using tungsten and sunlight is shown in Table I.

Table I

Comparison of Sunlight and Tungsten Sources for Measurement of Short Circuit Current on Irradiated Solar Cells

Solar Cell Nominal Base Resistivity	Type	Percent Change in I_{sc} after 10^{16} electrons/cm^2	
		Tungsten Light (100 mw/cm^2 sunlight equivalent)	Sunlight (100 mw/cm^2)
10 ohm-cm	N/P	37	26
1 ohm-cm	N/P	49	37
<1 ohm-cm	N/P	57	40
1 ohm-cm	P/N	76	63

These results show the extent to which the degradation in the long wavelength end of the response of the solar cells due to electron irradiation[2] is to be considered when analyzing data obtained from measurements on irradiated cells using a source other than sunlight. In the interpretation of the information presented here, it must be emphasized that tungsten operating at 2800°K is a "red" source, that is, the spectrum reaches a maximum near 1.0 micron (in the infrared region), while the sun is a "blue" source and peaks near 0.46 micron (in the blue). Since electron irradiation degrades the red end of the solar cell spectral response, radiation degradation appears worse under tungsten light than under sunlight.

As shown in Figure 3, the short circuit current does not change linearly with temperature; however, it is worthwhile to compare the change observed over the entire temperature range with respect to irradiation. The average short circuit current coefficient for a non-irradiated cell is 50.8μ A/°C, while for a cell irradiated to 10^{16} electrons/cm^2 it increases to an average of 69.8μ A/°C over the range -100°C to +100°C. This average is derived from data taken on all manufacturers' cells.

Short circuit current degradation as a function of irradiation has been adequately covered in an earlier report.(1) Since the results of the present study do not add to the data already presented except as previously mentioned, no further discussion need be given on this parameter.

Open Circuit Voltage

Open circuit voltage degradation as a function of flux level is shown in Figure 4 for both N/P and P/N solar cells. The N/P degradation points at each flux level represent an average of five different cells, while the P/N points at each level represent a single cell. The latter data should therefore be treated cautiously. Within the limits of the experiment no appreciable difference in radiation degradation of the open circuit voltage was observed between N/P cells of different base resistivities.

As shown in Figure 5, it was found that open circuit voltage, for both irradiated and non-irradiated (control) cells, decreased linearly with temperature over the entire test range. The average coefficient of open circuit voltage change with temperature was -2.34 mv/°C. The extremes were -2.16 mv/°C and -2.60 mv/°C. Since the variation noted appeared between individual cells of the same manufacturer rather than being manufacturer-dependent, it is probably due in large part to experimental error, but effects of real differences between cells (base resistivity effects, for example) are not considered negligible. For this reason, the average of -2.34 mv/°C is considered the appropriate choice for power supply design calculations. The temperature coefficient was also found to be independent of the level of irradiation as shown in Figure 5. Figure 6 depicts the percent change in open circuit voltage as a function of the percent change in short circuit current for both sunlight and tungsten sources at different irradiation levels for a nominal 1 ohm-cm solar cell. Figure 7 is a similar curve except that the cell has a nominal 10 ohm-cm base resistivity. The purpose of presenting these figures is to emphasize the fact that the degradation of open circuit voltage with irradiation must be considered in the design of a solar power supply.

Figure 8 shows the variation in peak power as a function of temperature and irradiation for a typical set of N/P cells under investigation. Peak power is somewhat meaningless to the power supply designer without reference to temperature, voltage and irradiation level, so no attemp will be made at this point to present detailed variations from one type of cell to another. In a later section of this report, curves will be presented which will allow the designer to determine peak power, taking into consideration the temperature and irradiation levels of interest. Specific values of radiation degradation of peak power at room temperature have been reported earlier.(1) Comparison between results obtained with tungsten light and sunlight as sources for measurement is given in Table II.

Table II

Comparison of Sunlight and Tungsten Sources
for Measurement of Peak Power
on Irradiated Solar Cells

Solar Cell Nominal Base Resistivity	Type	Percent Change in P_{max} after 10^{16} Electrons/cm^2	
		Tungsten Light (100 mw/cm^2 sunlight equivalent)	Sunlight (100 mw/cm^2)
10 ohm-cm	N/P	50.2	41.3
1 ohm-cm	N/P	58.2	47.6
<1 ohm-cm	N/P	65.2	47.4
1 ohm	P/N	85.5	78.0

P, V, T, and Φ Curves

In order to relate the appropriate solar cell electrical parameters for the power supply designer, curves have been drawn in the manner of Figure 9. These curves relate power (P), "operational" voltage (V), temperature (T), and flux level (Φ). The origin of this data is the set of I-V characteristic curves which were obtained during this investigation for temperatures between -100°C and +125°C in increments of 25°C. The power at each "operational" voltage is determined and the results are then combined to form the family of P, V, T, and Φ curves. In Figures 9, 10, and 11, the 1 Mev electron flux level and the operational voltage have been held constant so that is is possible to evaluate the effect of cell type and base resistivity on power output. As shown in Figure 9, where the cells have not been exposed to any hard particle irradiation, all the manufacturers' cells lie in a relatively narrow range. For the power supply designer, the P/N cell is the most appropriate choice here due to its higher open circuit voltage, which gives it a higher power over a wider temperature range. In Figure 10, irradiation has progressed to 10^{13} electrons/cm^2 and all cells with the exception of the severely degraded P/N cell lie in a close range of power output over the temperature range. Hence, if hard particle irradiation equivalent to the damage done by 1 Mev electrons at 10^{13} electrons/cm^2 were anticipated, the designer would be able to use most effectively the highest efficiency (as measured at room temperature) non-irradiated N/P cell available. Some cross-over will be noted at the higher temperatures; however, it is too early, in terms of irradiation, to see any distinct advantage of base resistivity. Progressing to 10^{16} electrons/cm^2, in Figure 11, there is a distinct advantage to the higher base resistivity cells. This advantage becomes less evident as the operational voltage is increased, and in fact, in extreme cases (high temperature) the 1 ohm-cm cell is the more desirable. The reason for this is the higher initial open circuit voltage of the 1 ohm-cm cell relative to the 10 ohm-cm cells among the cells under investigation. However, the solar cell would be operating in an extremely precarious and inefficient region of the P, V, T, and Φ curve in order to achieve any advantage of this characteristic. Figure 12 depicts this extreme situation on an expanded power scale and shows the 10 ohm-cm, 0.40 volt curve dropping inside the 0.40 volt, 1 ohm-cm curve. The 0.45 volt curves of this figure would have the same relationship if complete data were available for this region and hence are shown as such by extrapolation of the 0.45 volt, 10 ohm-cm curve. It should be kept in mind that choosing too high an operational voltage, combined with a low estimate of operating temperature, would be disastrous for the power supply because the curves have a steep slope relative to increasing temperature after the peak is achieved. In consequence of the foregoing, the next series of figures (13-21) present the available P, V, T, and Φ curves for the N/P, 1 and 10 ohm-cm cells only. (Although the 10 ohm-cm solar cell has been shown to be more radiation resistant and the preferred choice for the power supply designer in almost all circumstances, the 1 ohm-cm curves are presented because of continued use of this type of cell on solar power supplies.) These figures will directly aid the power supply designer who is designing a constant voltage supply (the most common in satellite use) in determining the most desirable operating voltage once he knows the 1 Mev electron flux equivalent and the operating temperature of the cell. Also, since these curves are derived directly from the I-V curves, they can be used (through cross-plotting) for any other mode of operation. The curves presented for irradiated cells, if used "as is," allow for a considerable margin of safety in that the source used in the investigation was tungsten.

In order to be useful to the spacecraft solar power supply designer, the data obtained during this investigation will have to be corrected to reflect the air mass zero operating environment. Also, extrapolations are necessary to reflect solar cell conversion efficiency improvements made by manufacturers since this project was initiated.

To correct the tungsten air mass 1 equivalent data (i.e., all P, V, T, and Φ curves in this report) to the air mass zero operating environment, both spectral and intensity adjustments must be made. Tungsten, as was indicated earlier, exaggerates I_{sc} damage seen on irradiated cells. To evaluate this difference, I_{sc} measurements were made under both tungsten light and sunlight on all cells. The results were then normalized to 100 mw/cm^2 and 30°C. The ratio of the short circuit currents under the two illumination conditions was obtained for each group of cells and is shown in Figure 22 for the 1 and 10 ohm-cm samples. Measurements indicate that this ratio holds, within experimental limits, throughout the temperature range. If the power value, on any of the P, V, T, and Φ curves is multiplied by this factor, taken at the appropriate flux level, the result is a sunlight air mass one, 100 mw/cm^2 value. The air mass zero intensity adjustment is made by obtaining the ratio of energy, in the solar cell response region, of the sunlight air mass zero spectrum to the sunlight air mass one spectrum, weighted according to the spectral response of the cells. This ratio has been determined[3] to be 1.17.*

The solar cell efficiency improvement correction is made by obtaining an I-V curve of the new non-irradiated cell at some convenient temperature and illumination condition. Similar information is extracted from the appropriate (1 or 10 ohm-cm) P, V, T, and Φ curve for the same temperature and illumination conditions. A ratio of the currents of the old and new cell at the constant voltage point of interest is then extracted from this data. All of the power values on the P, V, T, and Φ curves at this particular voltage can then be multiplied by this ratio to obtain a good estimate of the output from the improved cell. This correction may be applied only to cells which are similar, in terms of dopents, base resistivity, etc., to the ones under investigation in this report. Fortunately, most of the cells being used on today's power supplies fall into this category. The result of this correction will still yield a slightly conservative power figure in that additional improvements have been made in both the series resistance and open circuit voltage of the newer cells.

To summarize the above conversions:

$$P_2 = P_1 \left(\frac{I_S}{I_T}\right)\left(\frac{M_0}{M_1}\right)\left(\frac{I_2}{I_1}\right) \qquad (1)$$

*Different values ranging between 1.17 and 1.23 are in common use. The value 1.17 was chosen here because it represents a properly conservative approach to extrapolations.

where

P_2 = Power of the improved solar cell at air mass zero at the given conditions of temperature and irradiation.

P_1 = Power as measured under the tungsten air mass one equivalent conditions. This value is taken directly from the P, V, T, and Φ curves presented herein.

I_S = Sunlight short circuit current after irradiation at a given temperature and 100 mw/cm^2.

I_T = Tungsten short circuit current after irradiation at the same temperature as I_S (see Figure 22).

M_0 = Air mass zero energy in the solar cell response region weighted by the solar cell response.

M_1 = Air mass one energy in the solar cell response region weighted by the solar cell response.

I_1 = Current of the lower efficiency (old) cell at the desired operational voltage and some comparative temperature.

I_2 = Current of the higher efficiency (new) cell at the same operational voltage and temperature and under the same illumination conditions as I_1.

The use of the P, V, T, and Φ curves and the corrections described above are best illustrated with the aid of a design procedure description.

In this example, the solar array operating conditions have been predicted to be 0°C with a 1 Mev equivalent flux of 10^{15} electrons/cm^2 at end of mission.

1. The 10 ohm-cm cell is chosen due to the high 1 Mev flux equivalent. The P, V, T, and Φ curve which fits these conditions is found in Figure 20.
2. The optimum operational voltage is determined from Figure 20. In this case 0.45 volt is nearly optimum. (If more detail is required, power-voltage curves can be constructed from the given data.)
3. Correct the power at this voltage to reflect the air mass zero operating environment and the efficiency improvement on the newer cells using equation (1).

Conclusions

The following conclusions regarding the characteristics of 1962 state-of-the-art silicon solar cells bombarded under low level illumination and room temperature conditions by 1 Mev electrons have been obtained.

1. Post-irradiation measurements in the temperature range from -100°C to +125°C show N/P solar cells to be decidedly more radiation resistant than the 1 ohm-cm P/N cells.
2. Post-irradiation measurements in the temperature range from -100°C to +125°C show the nominal 10 ohm-cm N/P solar cells to have greater radiation resistance than the lower, 1 ohm-cm and less than 1 ohm-cm nominal base resistivity cells.
3. No single cell type (N/P or P/N; 1 ohm-cm or 10 ohm-cm base resistivity) can be chosen as the best cell (for power supply use)

for the entire range of irradiation from 0 to 10^{16} electrons/cm^2, the entire range of temperature from -100°C to +125°C, and the entire range of operating voltage. This results primarily from the fact that significant differences exist in the open circuit voltages of the various types of cells. However, the following generalizations can be made:

a. Prior to irradiation, P/N cells have better electrical power generating characteristics than N/P cells and the difference is most significant for higher operating voltages (above 0.35 volt/cell) and higher temperatures (above 50°C). This is primarily because of the higher open circuit voltage of the P/N cells.

b. After nominal irradiation (equivalent to 10^{13} electrons/cm^2), the overall higher radiation degradation rate of the P/N cells results in the loss of the advantage at the higher operating voltages and higher temperature conditions and also results in a disadvantage under low voltage and low temperature conditions. The amount of radiation is still not sufficient to produce a distinction between base resistivities in the N/P cells.

c. After extensive irradiation (equivalent to 10^{16} electrons/cm^2), the P/N cells are significantly poorer than any of the N/P cells under all conditions of temperature and operating voltage. The difference in radiation sensitivity is sufficient to clearly show the nominal 10 ohm-cm cells to be better than the nominal 1 or less than 1 ohm-cm cells except at the higher temperatures and higher voltages.

4. Degradation of open circuit voltage as a function of both 1 Mev electron flux and increasing temperature has a significant effect on the choice of operating voltage for a solar power supply.

a. The percentage degradation of open circuit voltage in sunlight with irradiation is roughly 1/2 the percentage degradation of short circuit current.

b. Open circuit voltage varies linearly with respect to temperature between -100 and +125°C for both irradiated and non-irradiated silicon solar cells.

c. The temperature coefficient of open circuit voltage is constant for any cell but varies from cell to cell. The average value is -2.34 mv/°C.

d. Irradiation does not appreciably affect the temperature coefficient of open circuit voltage in the temperature range from -100°C to +125°C.

5. Degradation of short circuit current with 1 Mev electron flux is significant, but variation with temperature is relatively unimportant.

a. Short circuit current increases but does not increase linearly over the temperature range from -100 to +100°C.

b. In general, the average temperature coefficient of short circuit current increases with increasing radiation. For non-irradiated 1 × 2 cm cells, the average coefficient is $50.8\mu A/^\circ C$ and for cells irradiated to 10^{16} electrons/cm^2, it is $69.8\mu A/^\circ C$.

6. Peak power generally decreases linearly above -50°C. Below -50°C, peak power is observed to increase, decrease and not change, depending on the cell. In most cases the change at temperatures below -50°C is small.

7. The P, V, T, and Φ curves represent a convenient aid to the solar power engineer, particularly in the design of constant voltage power supplies, but also in the design of power supplies operating in other modes. These curves show that at less than 10^{13} electrons/cm^2 the degradation is essentially the same for all N/P cells regardless of base resistivity. They also show that at irradiation levels above 10^{13} electrons/cm^2, the use of higher base resistivity cells is desirable.

BIBLIOGRAPHY

1. William R. Cherry and Luther W. Slifer, Jr., Solar Cell Radiation Damage Studies with 1 Mev Electrons and 4.6 Mev Protons, NASA-Goddard Space Flight Center, Greenbelt, Md., May 27, 1963.
2. William C. Cooley and Robert J. Janda, Handbook of Space Radiation Effects on Solar Cell Power Systems, Washington, D.C., Office of Scientific and Technical Information, NASA, 1963, p. 28.
3. Solar Cell Measurements, Hoffman Electronics Corporation, Semiconductor Division, El Monte, California, May 1960.

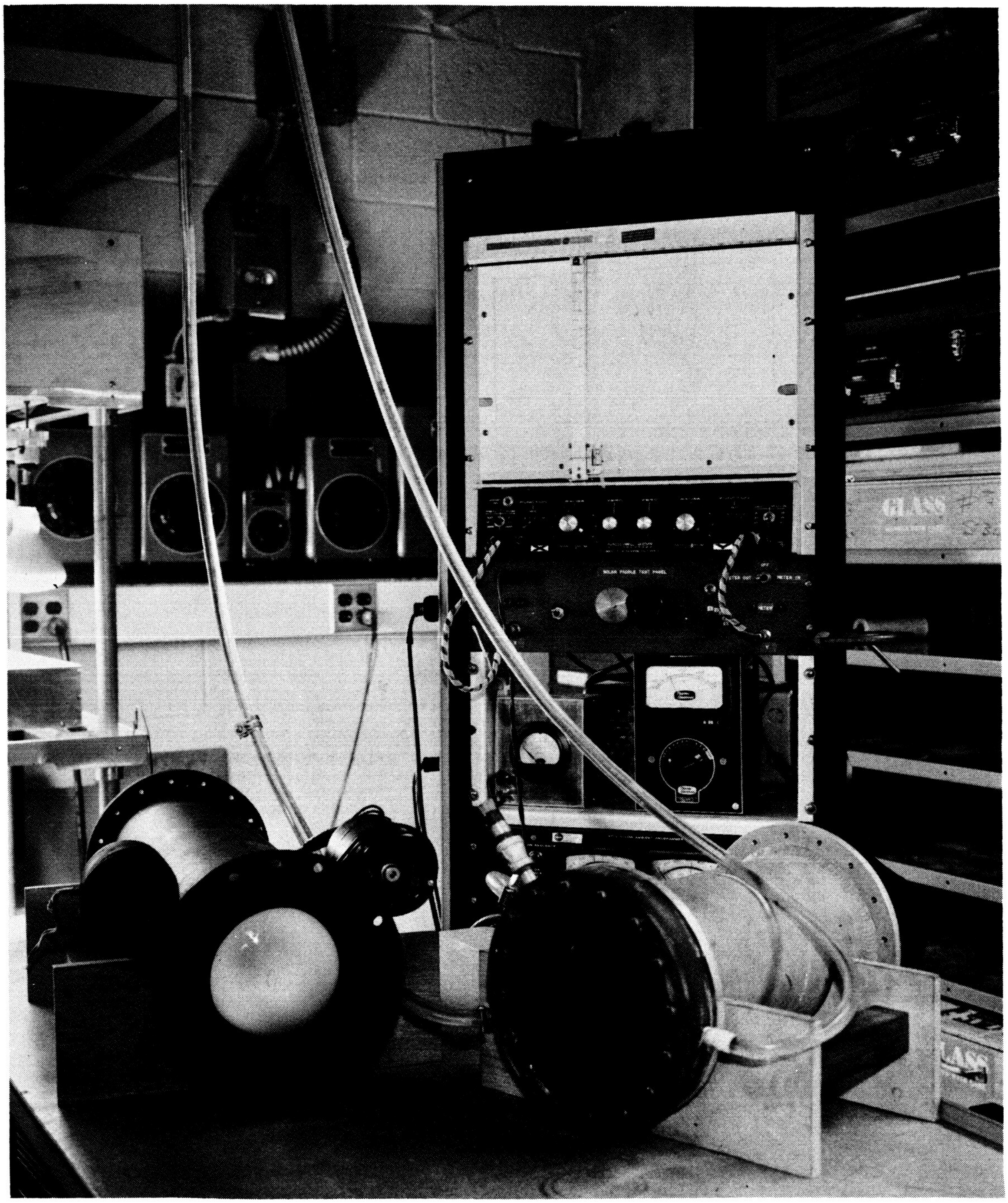

Figure 1 – Test Equipment

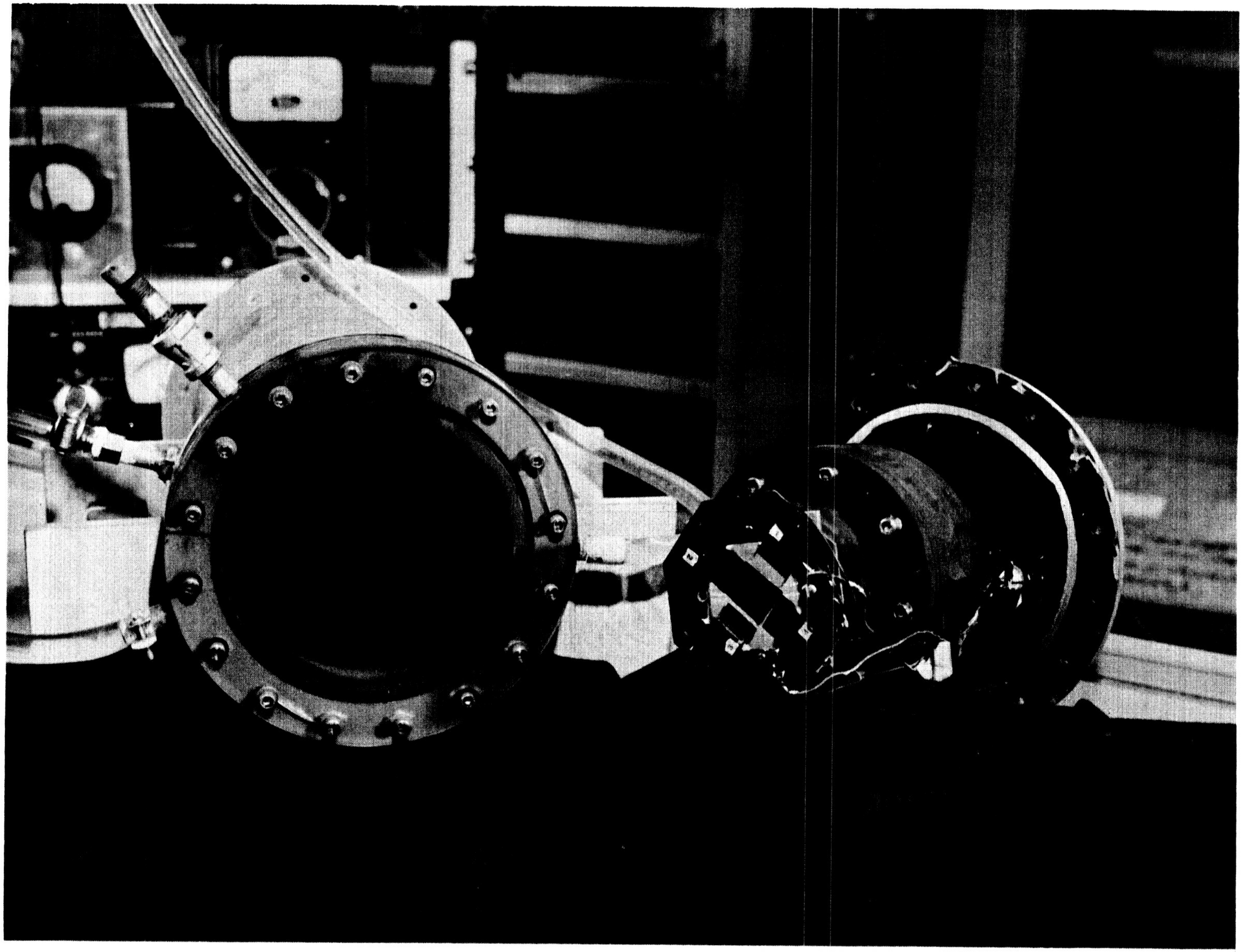

Figure 2—Temperature Control Block and Chamber

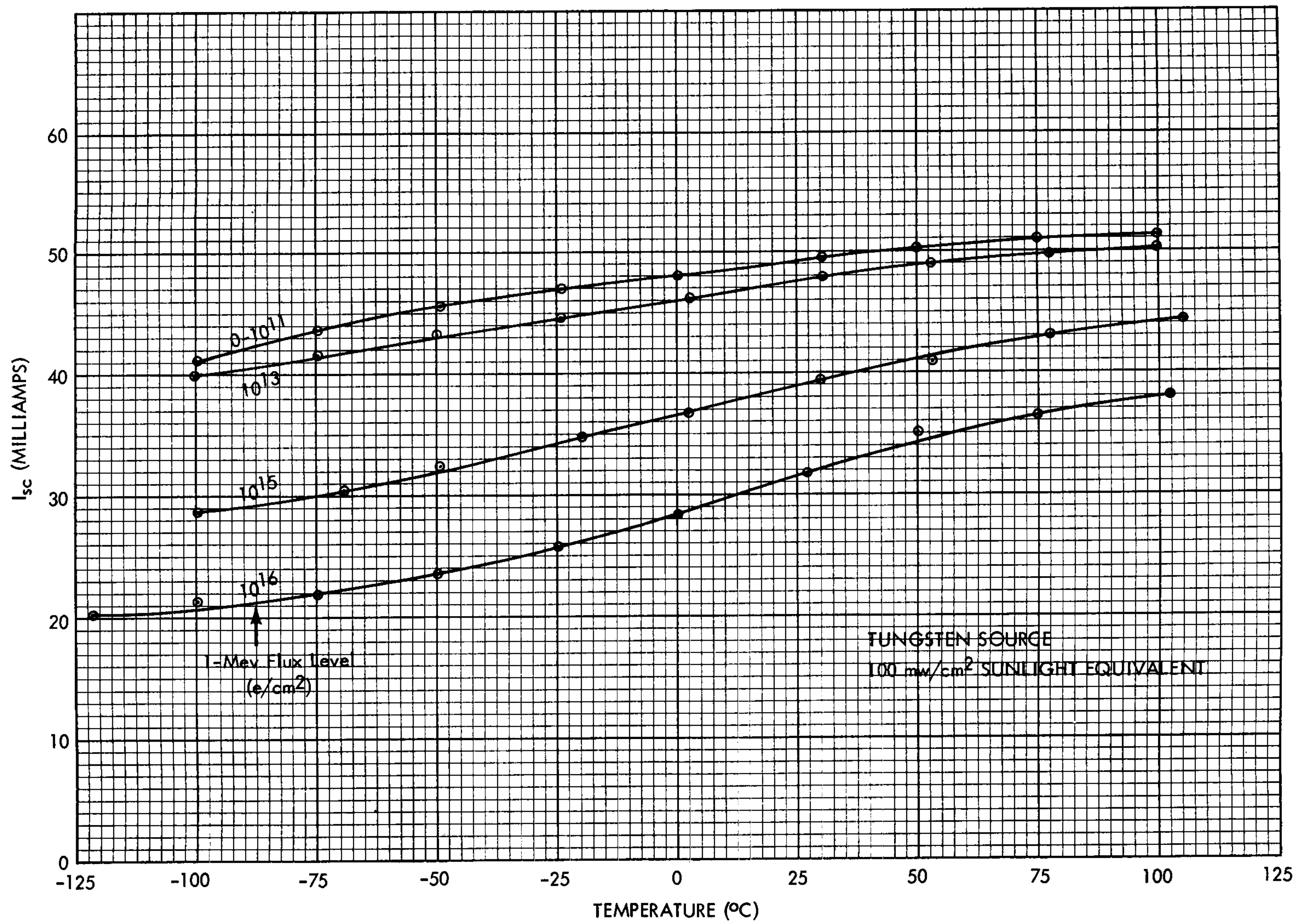

Figure 3–Effect of Temperature and Irradiation on Short Circuit Current (Typical Cells)

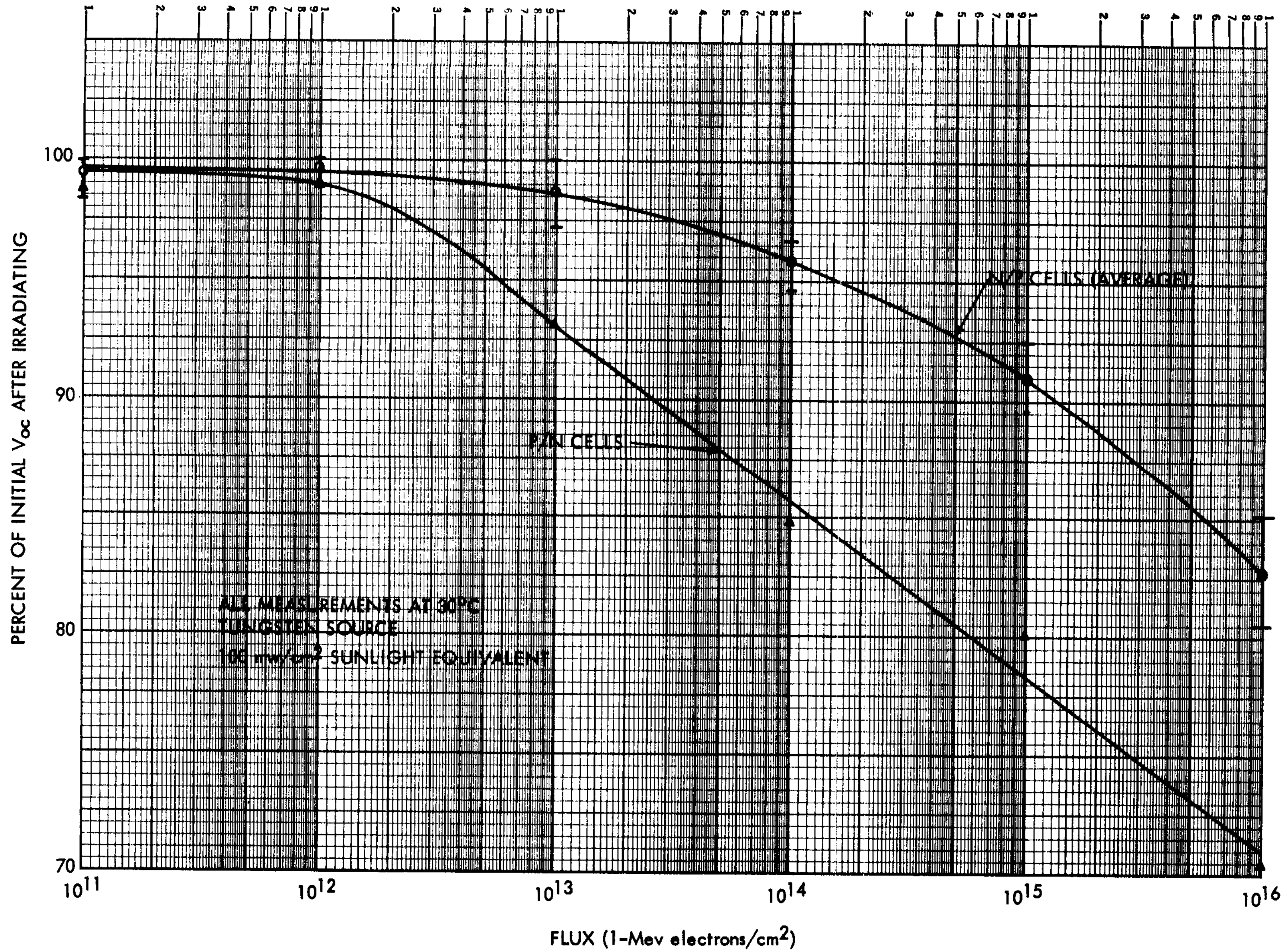

Figure 4—Degradation of Open Circuit Voltage

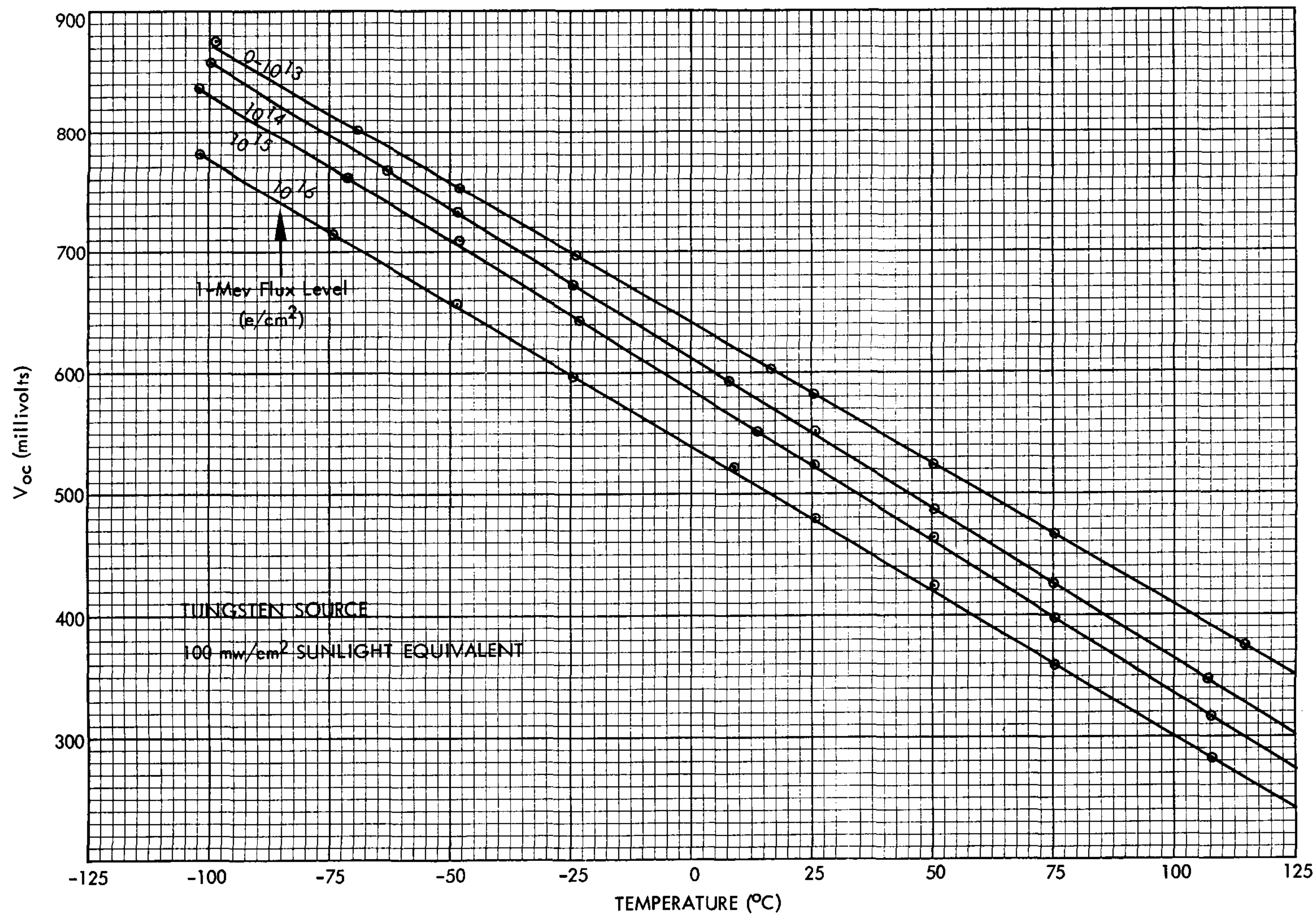

Figure 5–Effect of Temperature and Irradiation on Open Circuit Voltage (Typical Cells)

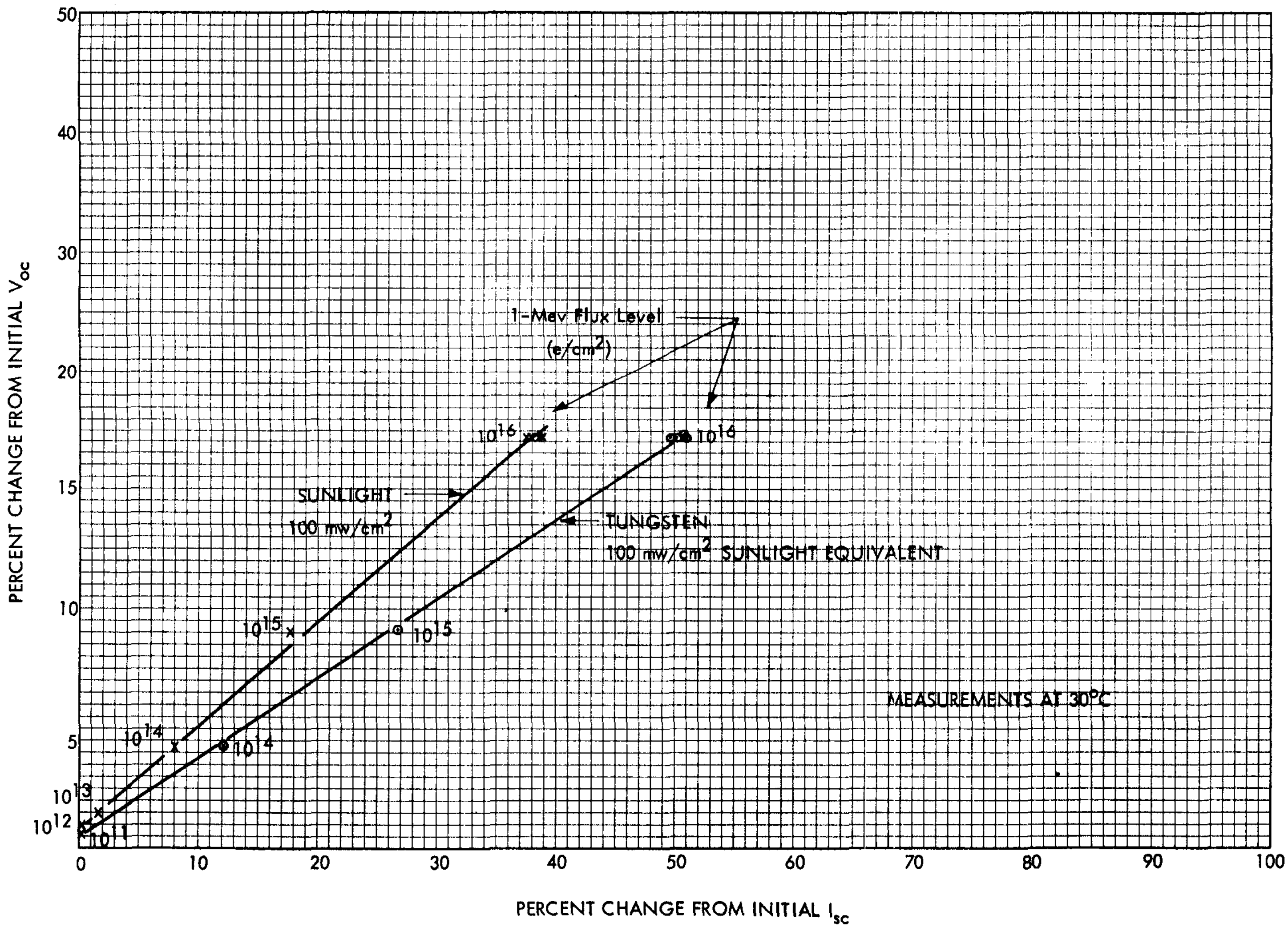

Figure 6—Comparison of Open Circuit Voltage Degradation to Short Circuit Current Degradation for Nominal 1 ohm-cm Cells

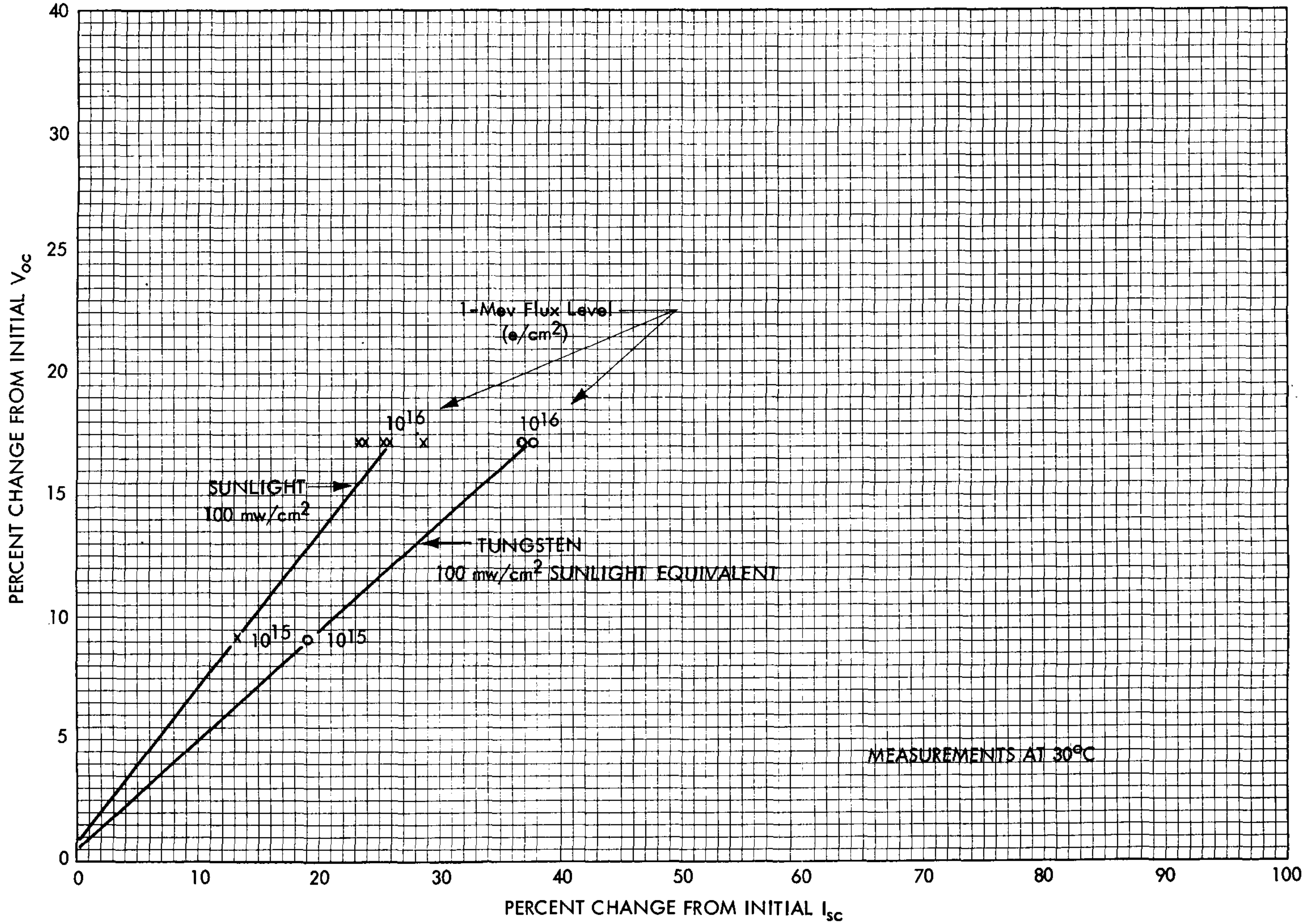

Figure 7–Comparison of Open Circuit Voltage Degradation to Short Circuit Current Degradation for Nominal 10 ohm-cm Cells

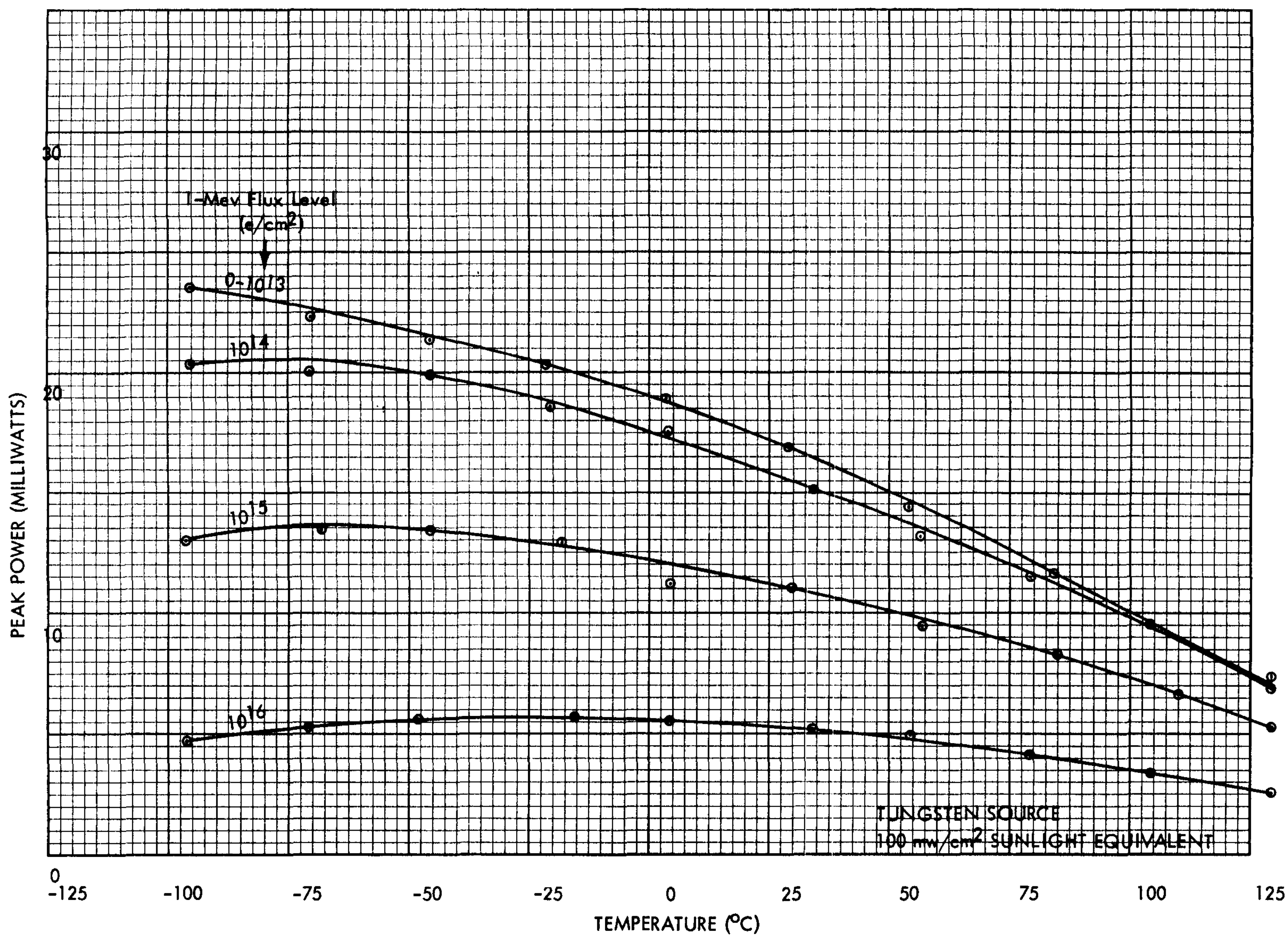

Figure 8—Effect of Temperature and Irradiation on Peak Power (Typical Cells)

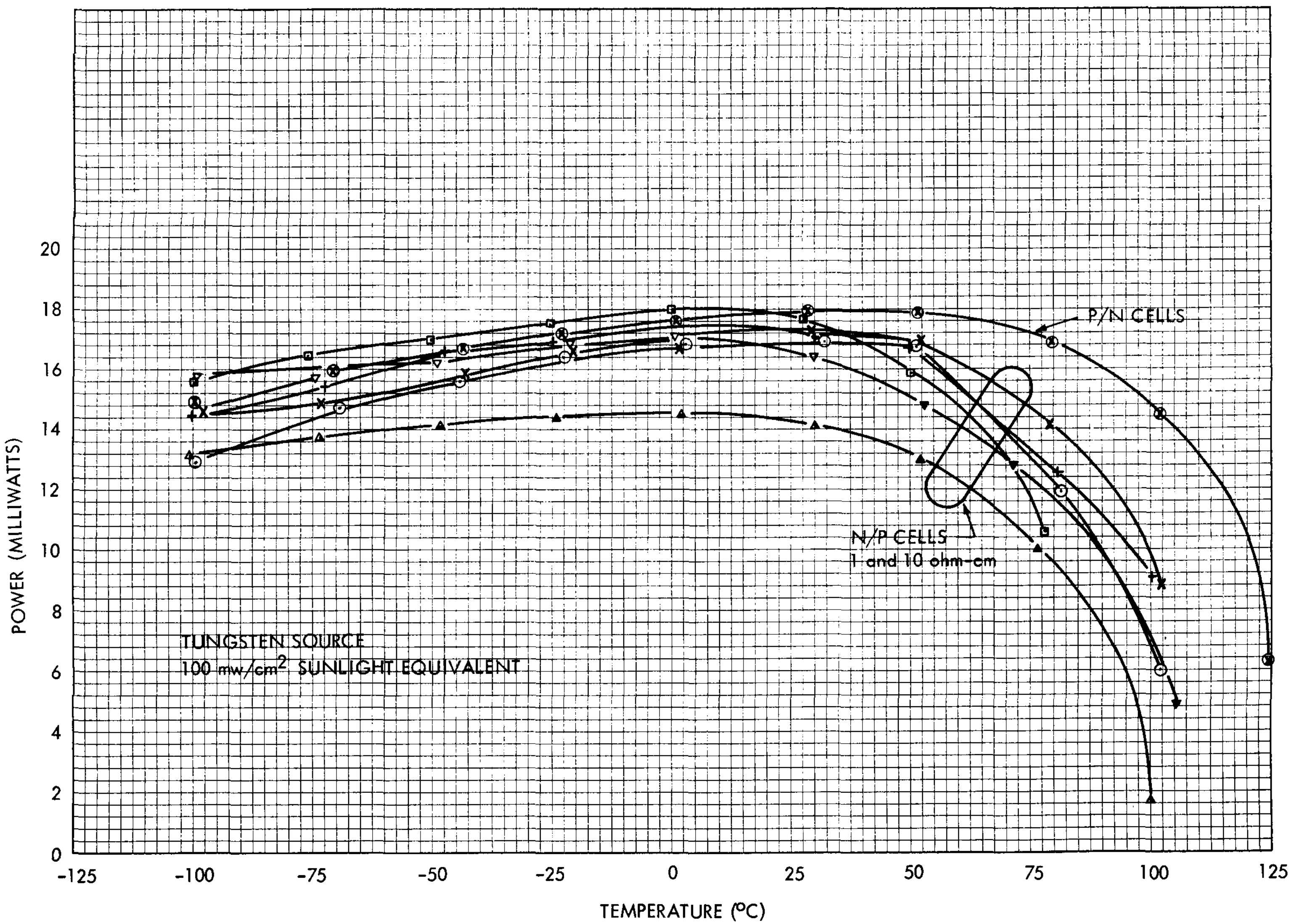

Figure 9—Comparison of Power Output for Non-Irradiated Solar Cells at 0.35 Volts

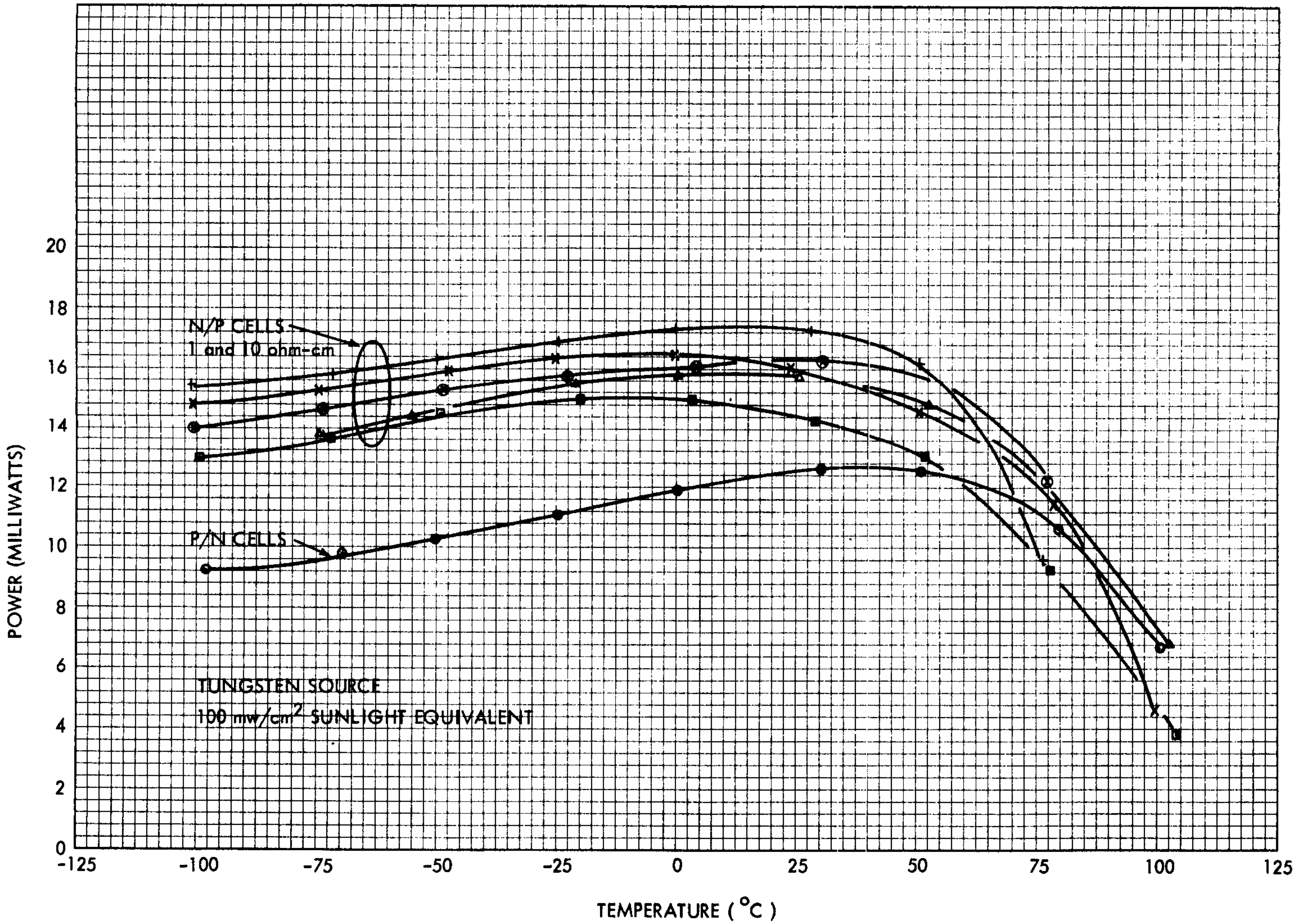

Figure 10—Comparison of Power Output at 0.35 Volts for Solar Cells Irradiated with 1 Mev Electrons to 10^{13} Electrons/cm^2

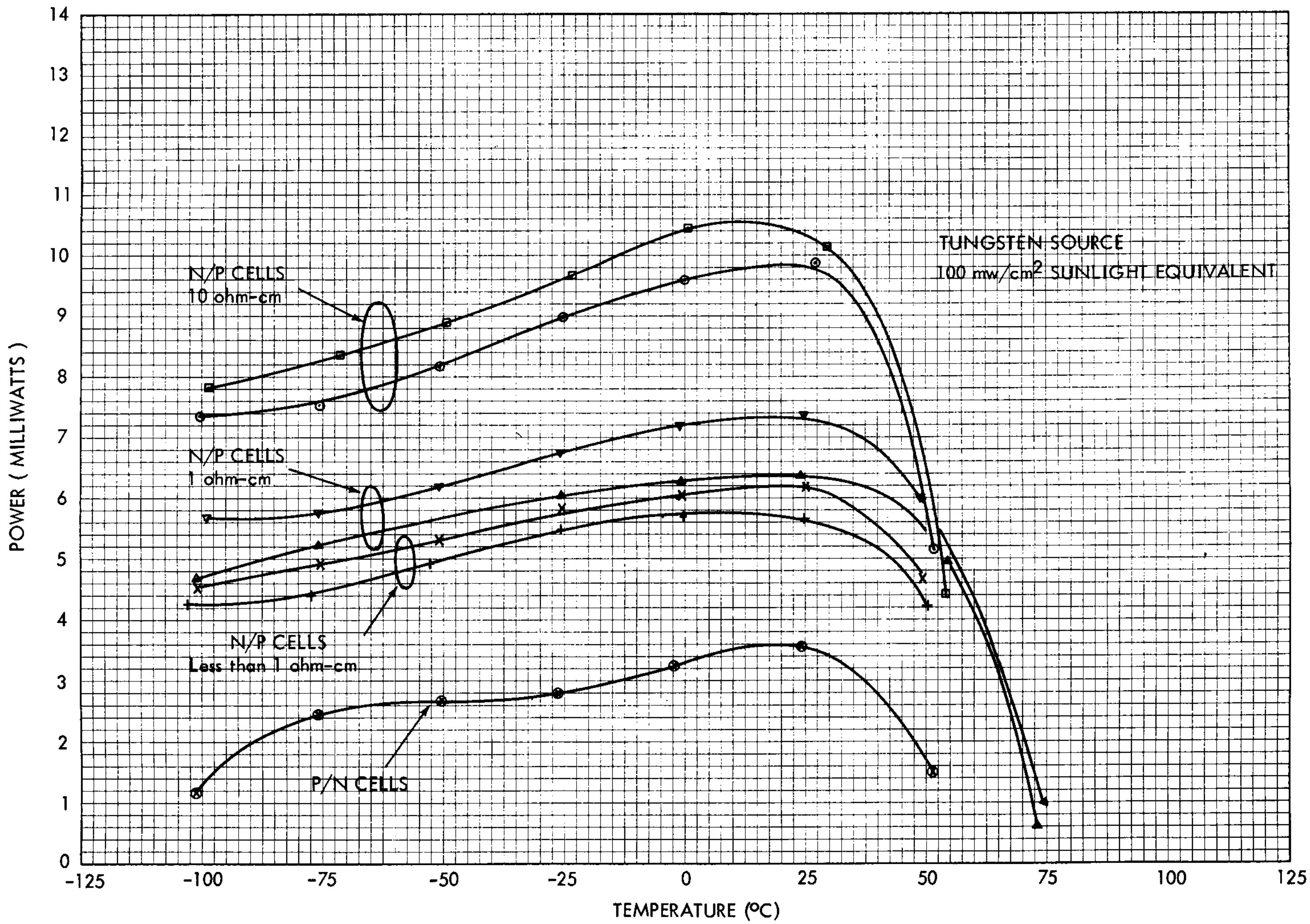

Figure 11—Comparison of Power Output at 0.35 Volts for Solar Cells Irradiated with 1 Mev Electrons to 10^{16} Electrons/cm^2

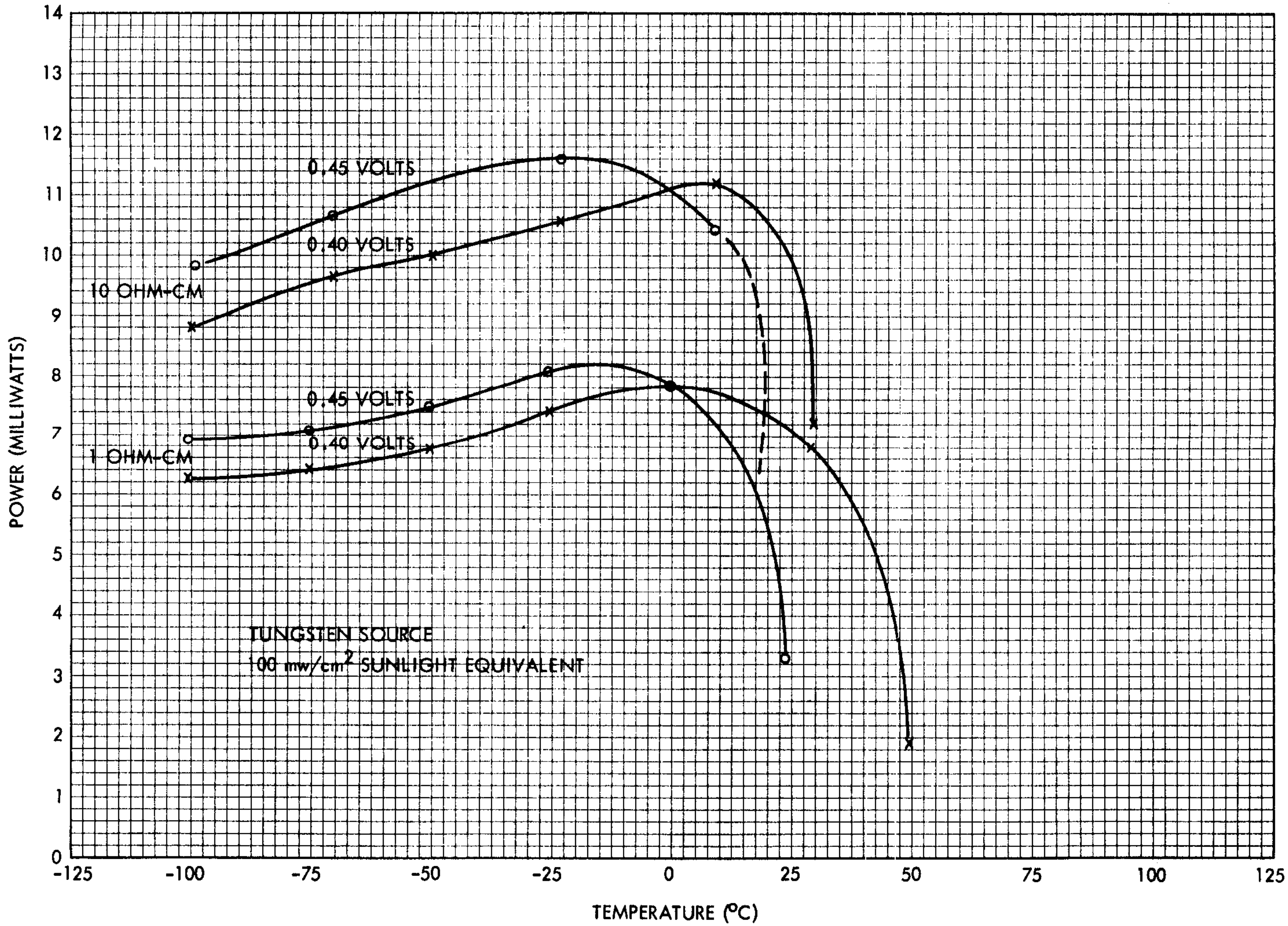

Figure 12—Comparison of 1 and 10 Ohm-Cm Solar Cell Power Output at 0.40 and 0.45 Volts After Irradiation to 10^{16} electrons/cm^2

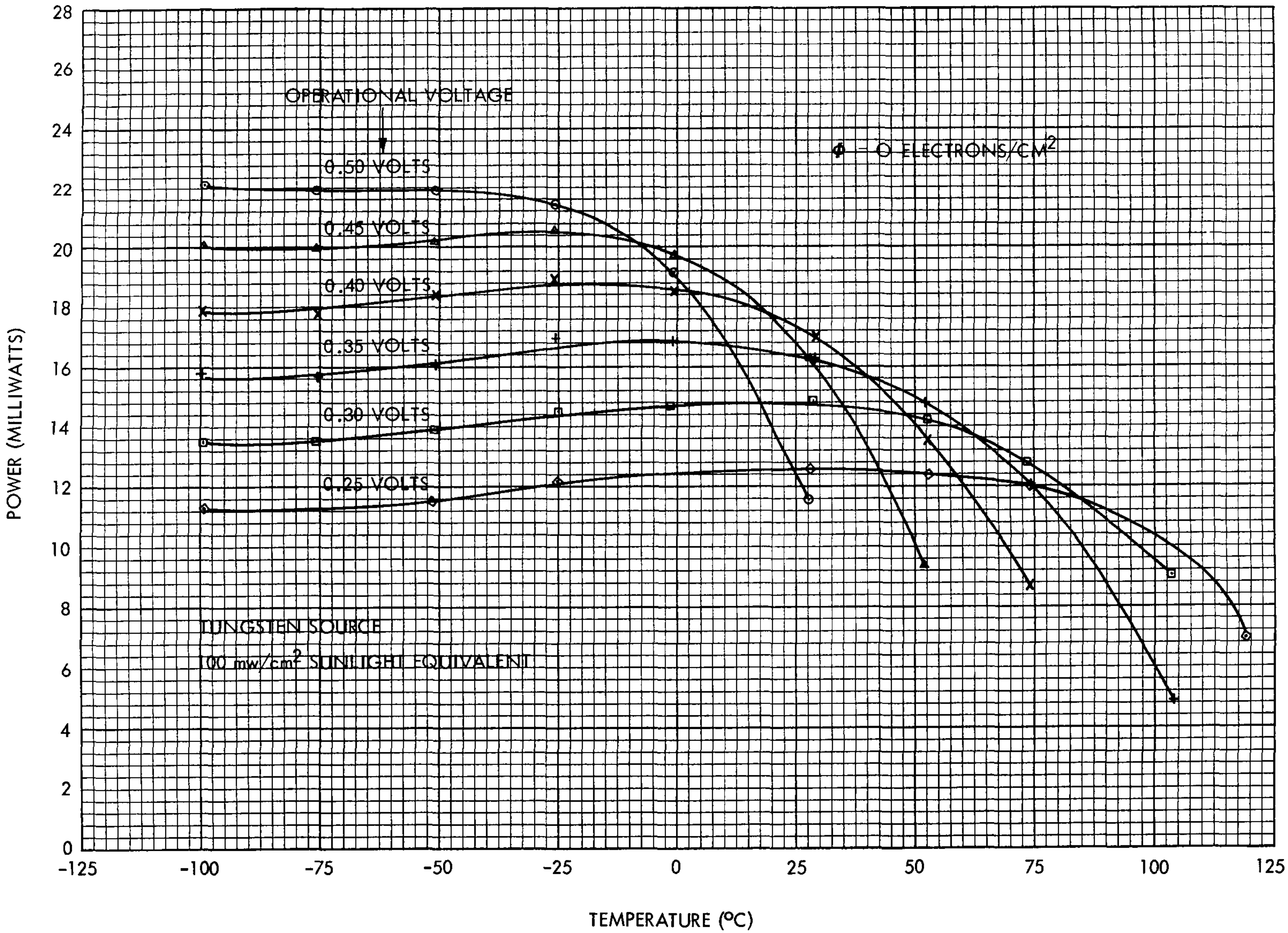

Figure 13–P, V, T ϕ Curves for a 1 Ohm-Cm N/P Cell with $\phi = 0$ Electrons/cm^2

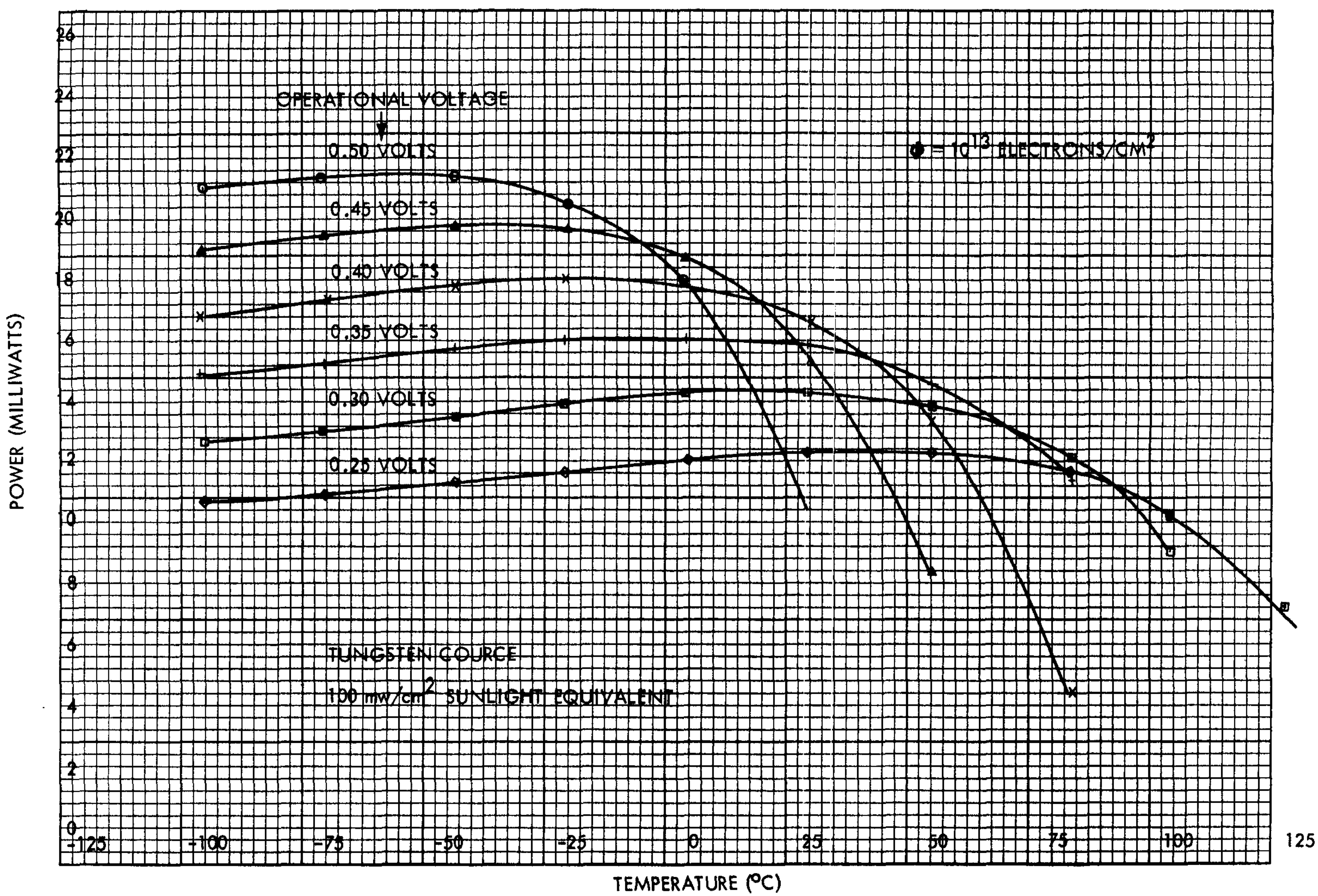

Figure 14—P, V, T, ϕ Curves for a 1 Ohm-Cm N/P Cell with $\phi = 10^{13}$ Electrons/cm^2

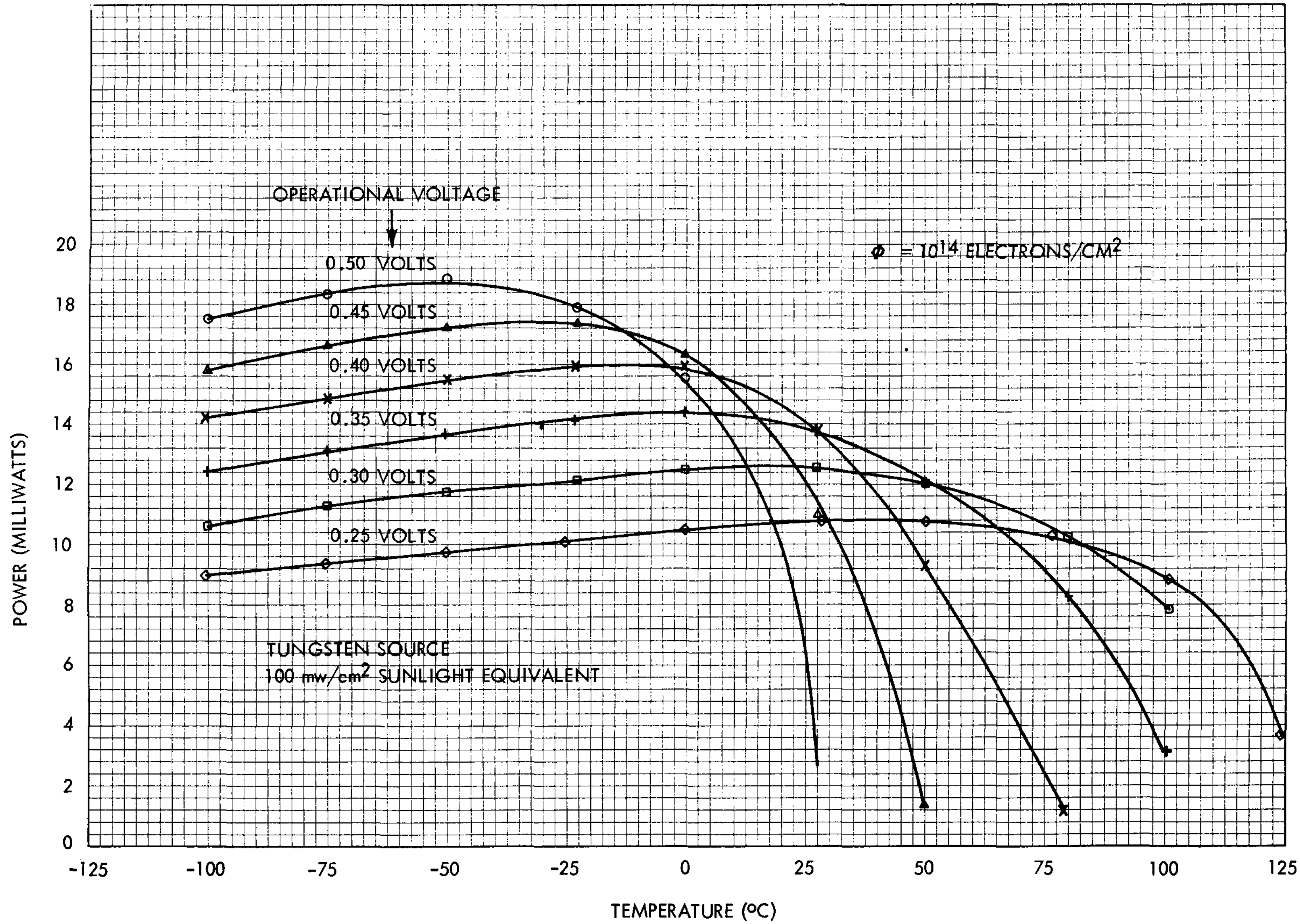

Figure 15–P, V, T, ϕ Curves for a 1 Ohm-Cm N/P Cell with $\phi = 10^{14}$ Electrons/cm^2

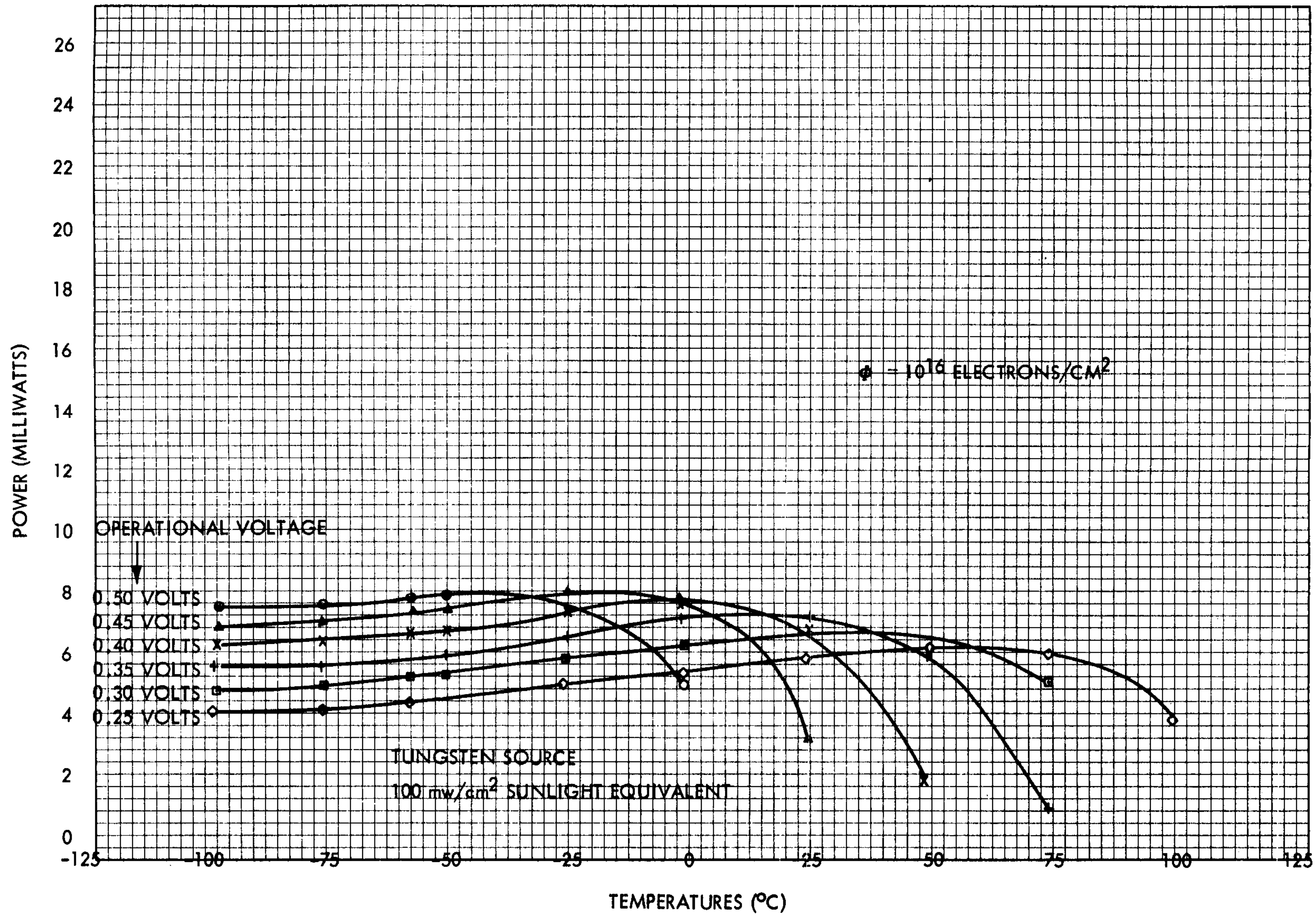

Figure 16—P, V, T, ϕ Curves for a 1 Ohm-Cm N/P Cell with $\phi = 10^{16}$ Electrons/cm²

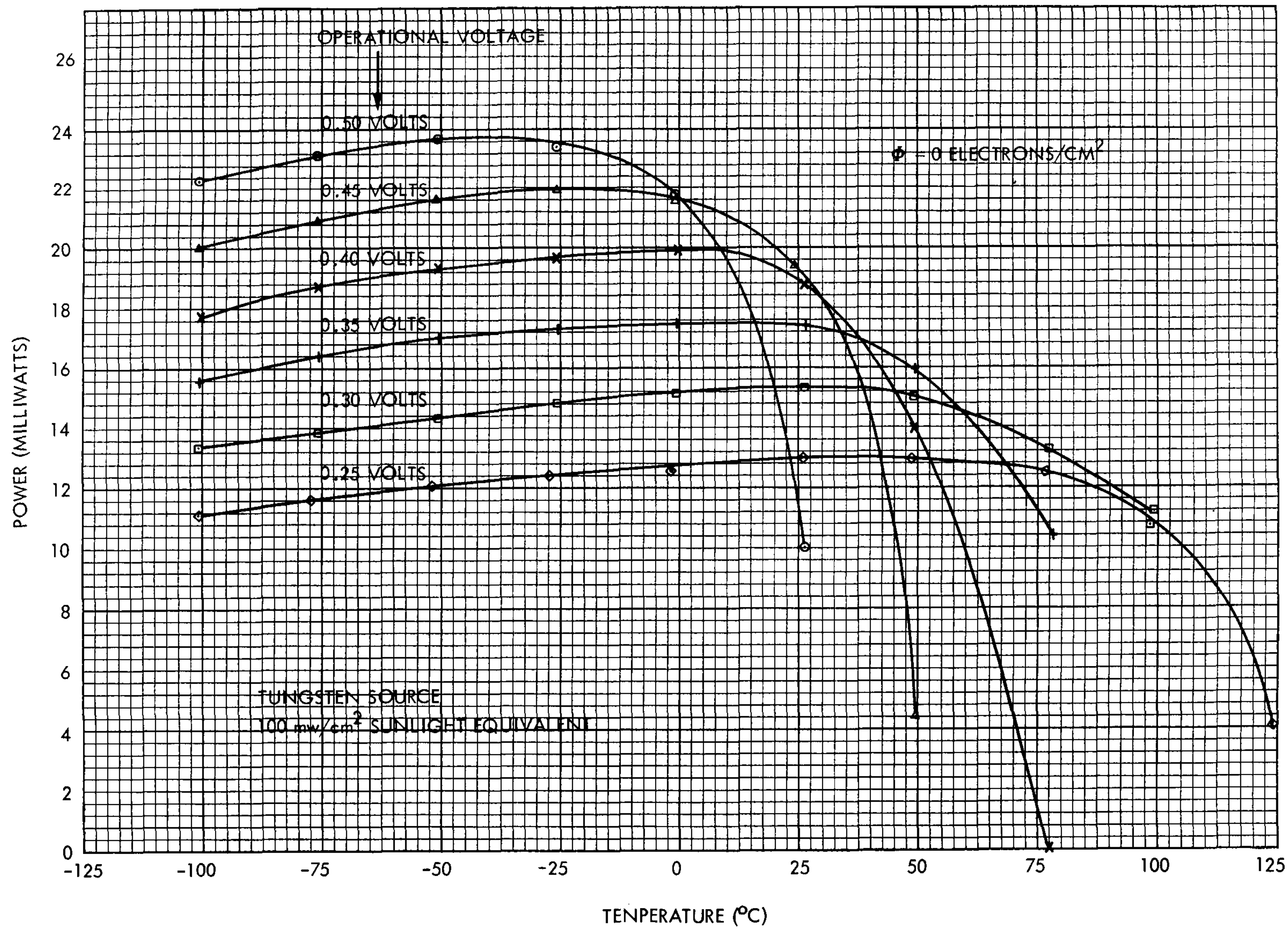

Figure 17—P, V, T, ϕ Curves for a 10 Ohm-Cm N/P Cell with ϕ = 0 Electrons/cm^2

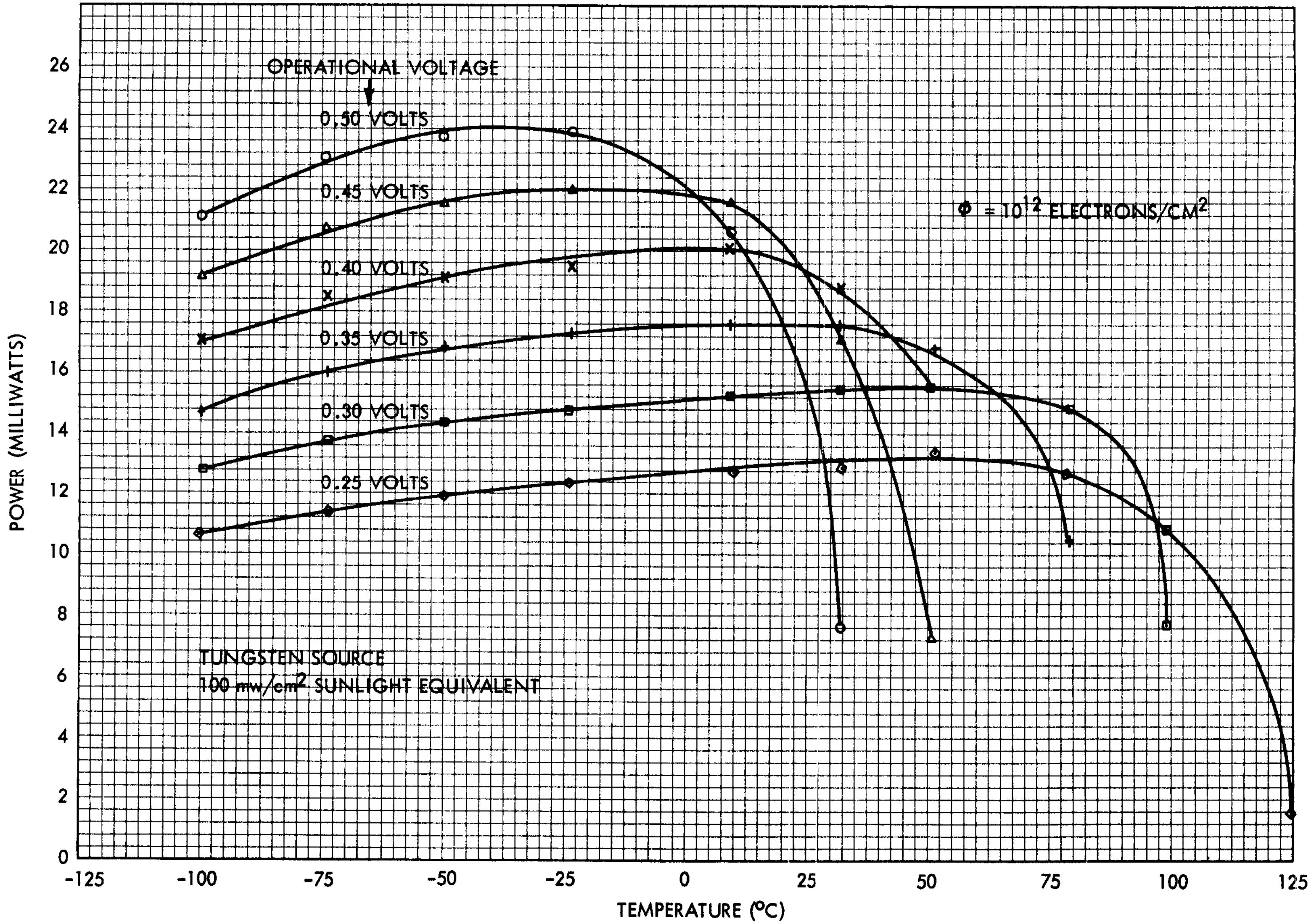

Figure 18—P, V, T, ϕ Curves for a 10 Ohm-Cm N/P Cell with $\phi = 10^{12}$ Electrons/cm^2

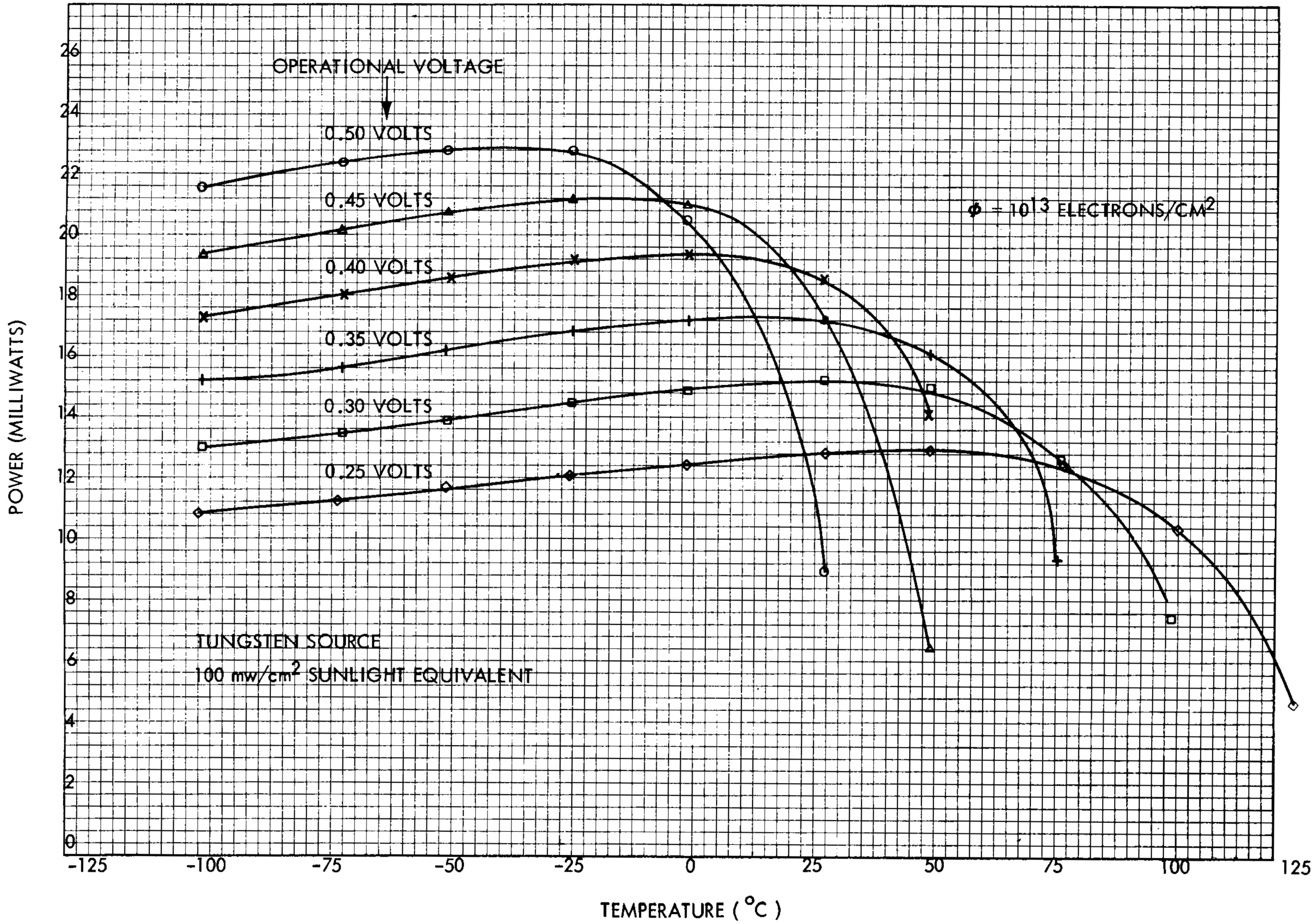

Figure 19–P, V, T, ϕ Curves for a 10 Ohm-Cm N/P Cell with ϕ = 10^{13} Electrons/cm^2

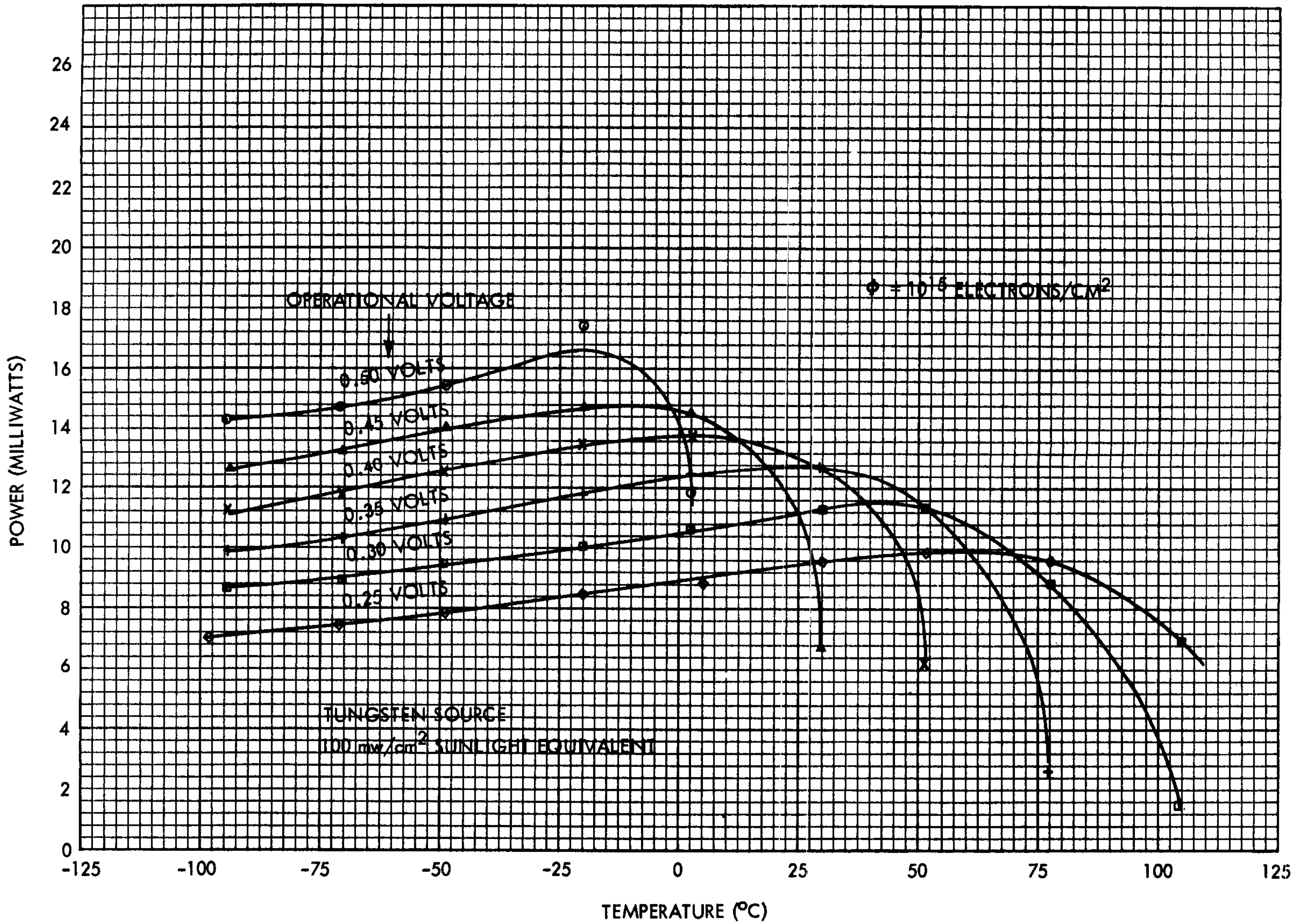

Figure 20—P, V, T, ϕ Curves for a 10 Ohm-Cm N/P Cell with $\phi = 10^{15}$ Electrons/cm^2

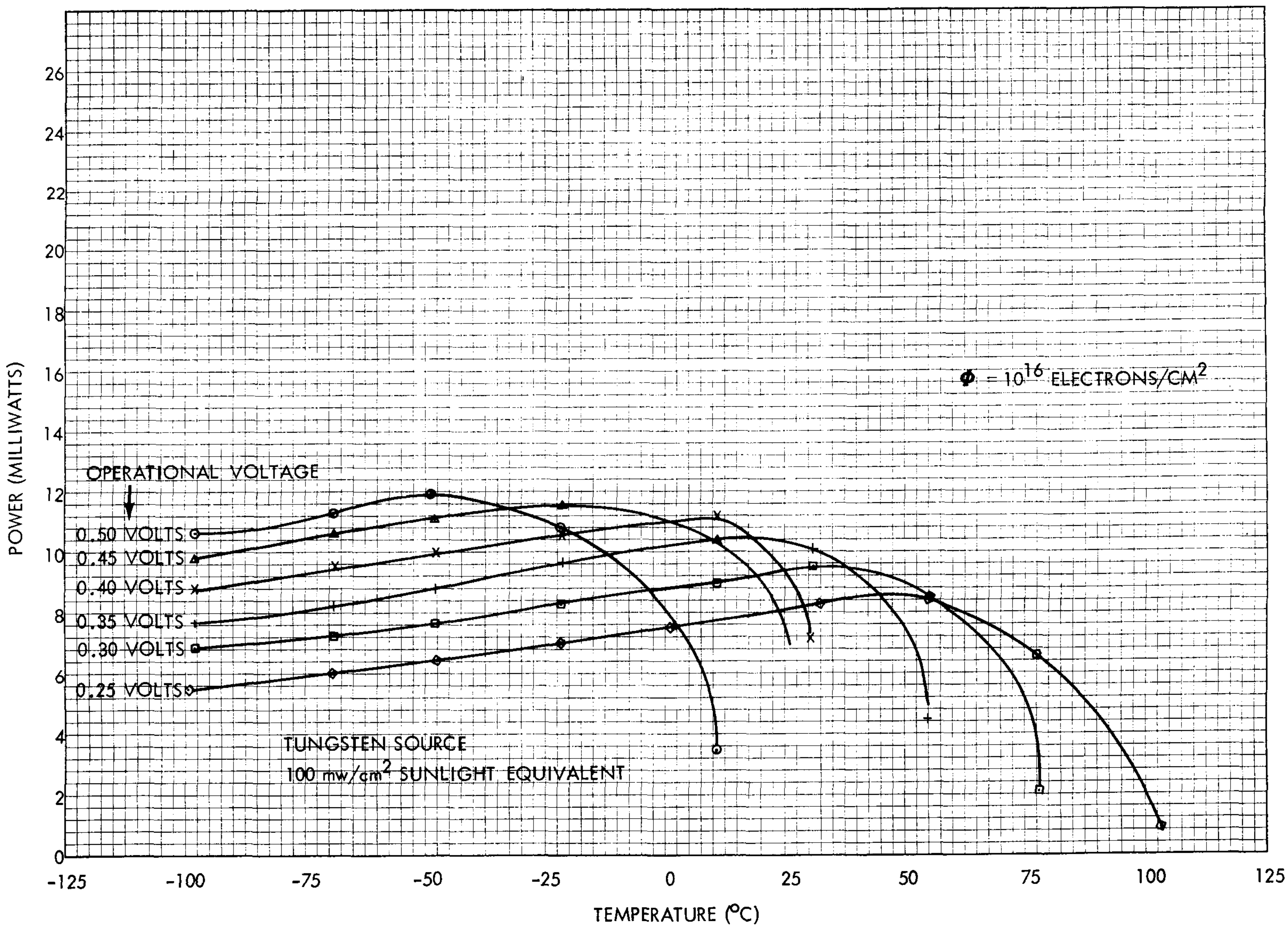

Figure 21 – P, V, T, ϕ Curves for a 10 Ohm-Cm N/P Cell with $\phi = 10^{16}$ Electrons/cm²

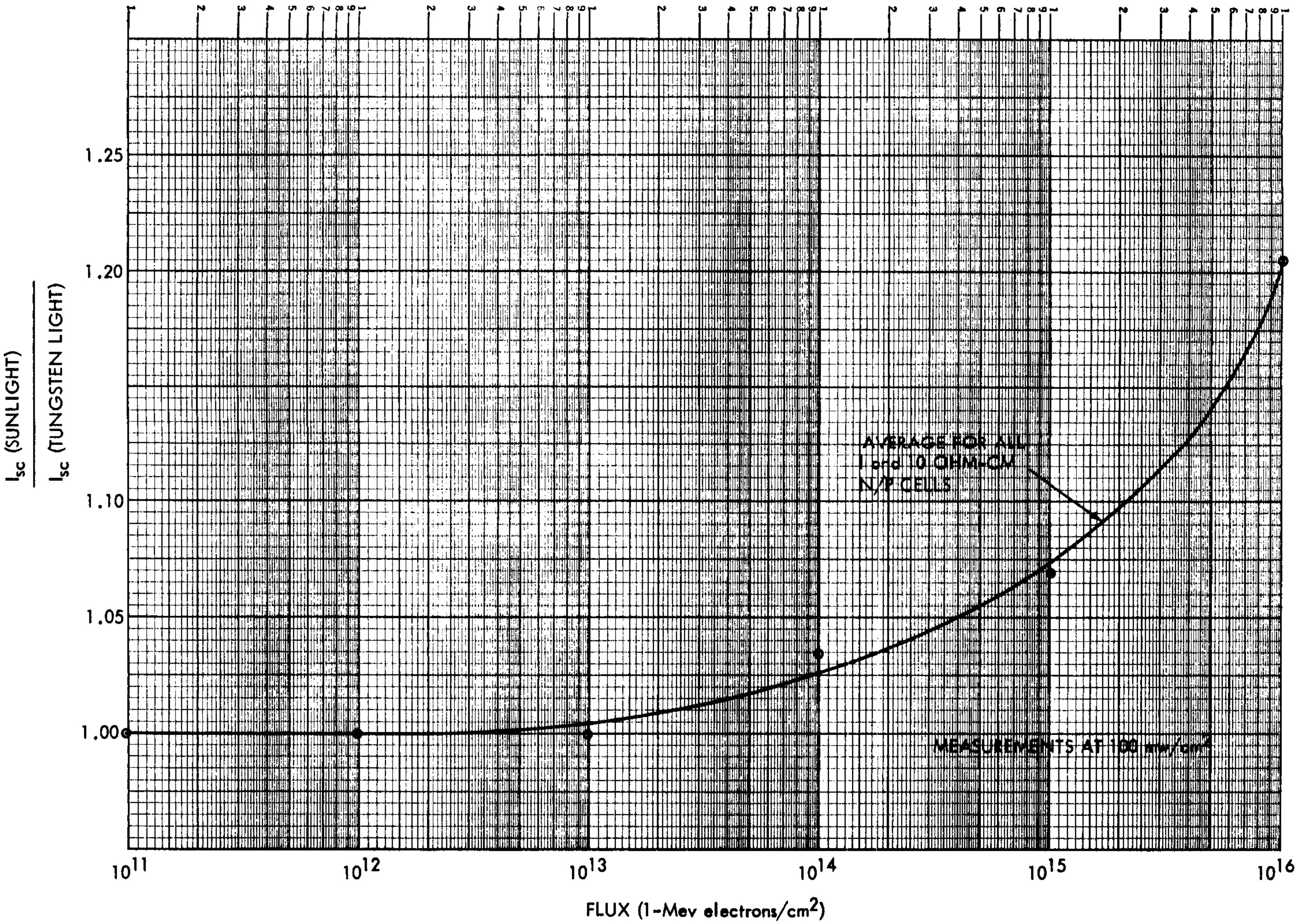

Figure 22—Ratio of Short Circuit Current in Sunlight to Short Circuit Current in Tungsten Light—After Degradation